NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

FREE SPACE OPTICAL COMMUNICATION FOR TACTICAL OPERATIONS

by

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September 2016

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2016	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE FREE SPACE OPTICAL COMMUNICATION FOR TACTICAL OPERATIONS	**5. FUNDING NUMBERS** N/A
6. AUTHOR(S) Jin Wei Lai	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School, Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER** N/A

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

The increasing demand for data bandwidth is a present and relevant issue for communications. Military communications further require secure connections for data transfer. The Free Space Optical (FSO) communication system, with its ability to connect at a high data rate, offers an appealing solution to the current need. Using laser technology and transmitting at a wavelength invisible to the human eye, FSO is difficult to detect and intercept, providing a highly secure means of communication. However, it faces the limitation of being a strictly line-of-sight communication technology and is known to be greatly affected by atmospheric attenuation.

This thesis documents three experiments involving FSO technology, including the process of the experiment preparations, laser-related hazard assessment, and implementation of a standard procedure to mitigate any possible risk. The contribution of this thesis is the acknowledgment that this proposed process is feasible.

Experiments were conducted on an SA Photonics NEXUS 3 FSO Communications System. From the gathered results, the system was assessed to provide high throughput and low frame loss. Our work also ascertains that FSO is a technology that can become the next-generation means of military communications. Specifically, our findings indicate that the NEXUS has potential and merits further testing and development for military communications.

14. SUBJECT TERMS free space optics, communications, computer science, networking, laser communications	**15. NUMBER OF PAGES** 93
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 | Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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FREE SPACE OPTICAL COMMUNICATION FOR TACTICAL OPERATIONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
September 2016

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LIST OF ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
CD	Compact Disc
EMI	Electromagnetic Interference
FSO	Free Space Optics/Optical
IR	Infrared
JIFX	Joint Interagency Field Experiment
LHAZ	Laser Hazard Analysis Software
LOS	Line of Sight
LSRB	Laser Safety Review Board
MPE	Maximum Permissible Exposure
NOHD	Nominal Ocular Hazard Distance
NPS	Naval Postgraduate School
ORM	Operational Risk Management
RF	Radio Frequency
RFI	Radio Frequency Interference
ROM	Read-Only Memory
SOP	Standard operating Procedure

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ACKNOWLEDGMENTS

First and foremost, I would like to gratefully and sincerely thank his thesis advisor, Mr. John H. Gibson, for his kind understanding, relentless patience, and valuable guidance. Despite the short amount of time, Mr. Gibson was willing to provide me with the opportunity to embark on this journey. He has been consistent in ensuring I had all the support required for the thesis to be continuous and smooth. His mentorship has been paramount in providing a fruitful learning experience, leading to a success in my thesis.

Next, I truly appreciate my co-advisor, Dr. Gurminder Singh, for his assistance and guidance during the course of this thesis. I would like to thank him for placing trust in my ability to complete the thesis under time constraints. I would like to thank SA Photonics and its team for their selfless support during the JIFX trial. The team has been a great pleasure to work with. I would also like to thank Mr. Scott Giles for his support and guidance for the laser-related knowledge sharing. I also appreciate the International Graduate Programs Office and Thesis Processing Office for their support and services.

I would like to extend my gratitude to Singapore Technologies Kinetics Ltd. for providing me with the opportunity to embark on this 18-month master's program. Special appreciation goes to my superiors—Mr. Toh Beng Khoon (SVP, GM KDM), Mr. Yeo Beng Hai (VP, Head Engineering), Mr. Ang Leng Seng (VP, Head VSC), Mr. Yeo Chin Liong (PE, System Head), Mr. Eng Chun Heong Dave (PE, System Head), and Ms. Yeo Huei Yan Hazel (AM, HR)—for their encouragement and support in my pursuit of this study. I am thankful for them making special arrangements to ensure I could focus on my personal development.

Most importantly, I would like to dedicate my heartfelt appreciation to my wife, Ms. Foo Suan Wood, and my family, Mr. Lai Lin Wah (father), Ms. Chin Choon Heong (mother), and Ms. Lai Mei San Jessica, for their unconditional support, care, and concern through the course of my studies. I would not have achieved what I set out to do without their assistance, especially my wife, who has selflessly put aside her career in order to accompany me and take care of me during this year in Monterey. My family's love has been instrumental to my successful completion of this double degree over the span of 18 months.

Finally, the author would like to thank my Singaporean course mates, Major Lai Guoquan John and Mr. Zhang Zhibin, for their assistance in the completion of my master's degree in computer science. I would also like to thank my community of Singaporeans in Monterey. They have offered me help and company whenever I was in need. This community provided me with the constant feeling of being back in my home country, Singapore. The stay in the United States would not have been so remarkable without them in it together.

I. INTRODUCTION

Demand for bandwidth in data communications is increasing exponentially, particularly in light of advancing high-definition video capture and processing capabilities. This upward trend suggests the demand is unlikely to plateau. Communication is no longer defined as solely voice or text chatting, but has shifted to also include transferring large amounts of data. In the past, communications between two parties were satisfied by a voice call or a simple text message. However, in this age and time, communications are enhanced to include high resolution images, videos and on-air video conferencing. It is likewise for military communications. Images or videos may be streamed from the action zone back to the planning team for dynamic mission planning. In order to support this mode of communication, a high bandwidth communication technology is needed.

In commercial infrastructure where on-the-move mobile communications is not a constraint, the solution is fiber-optic technology. However, that solution is infeasible for networks employed during tactical operations, which almost always require on-the-move wireless communications. Radio frequency (RF) communication is used to fill the gap, but RF systems are hard pressed to meet the current bandwidth demands. Furthermore, RF is vulnerable to security threats and susceptible to electromagnetic interference (EMI).

A potential solution is Free Space Optical (FSO) communication, which relies on laser technology to provide fiber-like performance capabilities. Furthermore, FSO communication offers higher levels of security and is immune to EMI. Nevertheless, it poses some shortfalls and limitations; these include susceptibility to varying weather conditions like heat from the ground and heavy fog or dust.

In this thesis, experiments were conducted for a FSO communications system to understand its network performance over different link range. Analysis from the data collected showed that the system is capable of sending and receiving 4.7 Gbps of Ethernet load using a 10 Gbps data stream over a link range of 9 km with a mean percentage frame loss of 0.23%.

A. PROBLEM STATEMENT

It is evident that the next generation of communication technology has to be sought for military tactical use. The FSO communication system fits the criterion to address the demand for increased bandwidth required in present operations. Hence, it is necessary to understand the network performance of this system and the parameters that affect its functionality.

B. OBJECTIVES

The key objectives of this thesis are (1) to understand FSO and explore its advantages and limitations; (2) to design field experiment tests for evaluation of a given FSO communications system; (3) to conduct the designed experiment and analyze the collected results. The thesis aims to provide a proper guide to conduct experiments pertaining to a laser communications system and to provide a fair analysis of the FSO product’s network performance.

C. SCOPE

This thesis focuses primarily on experimenting with a commercial-off-the-shelf FSO communication system based on a thoughtfully designed experimental plan and procedure to ensure safety for personnel and the system itself. This thesis also explores the feasibility of laser communications and suggests potential future work.

D. ORGANIZATION OF THESIS

The thesis begins with an acknowledgement of the present day challenge posed by the lack of bandwidth for communications systems and what this thesis aims to achieve. Chapter II provides a background of FSO, the science behind it, and also discusses its advantages and challenges.

The heart of the thesis lies in Chapter III where the preparation of the experiment is described. The author proposes an organized approach to prepare for the experiment. This includes the development of experimental plans and procedures, as well as a description of the process for acquiring required approval for Navy and Naval Postgraduate School (NPS) FSO trials. Chapter IV plays a critical role as it documents the execution of the experiments and performs an analysis based on the performance parameters of the FSO product used to conduct the experiments.

The thesis ends with a conclusion based on the stated objectives and recommends potential future work that could further the cause of this thesis.

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II. BACKGROUND

This chapter provides background related to the technology upon which this thesis is focused—Free Space Optical Communication. The first part of this chapter discusses the science behind FSO technology. Next, some of the parameters critical for FSO and related to this thesis are featured. Finally, the advantages and challenges pertaining to FSO are discussed.

A. SCIENCE

FSO is a communication technology that employs connections over the optical bandwidth to use light as its means to transmit or receive data with air as its medium [1]. This technology is also commonly known as laser communication. FSO operates in the range of 780–1600 nm wavelengths and is capable of data transmission of up to 2.5 Gbps [2].

Like any communication system, FSO requires two basic modules—a transmitter and a receiver. Figure 1 shows the basic system behind FSO communication.

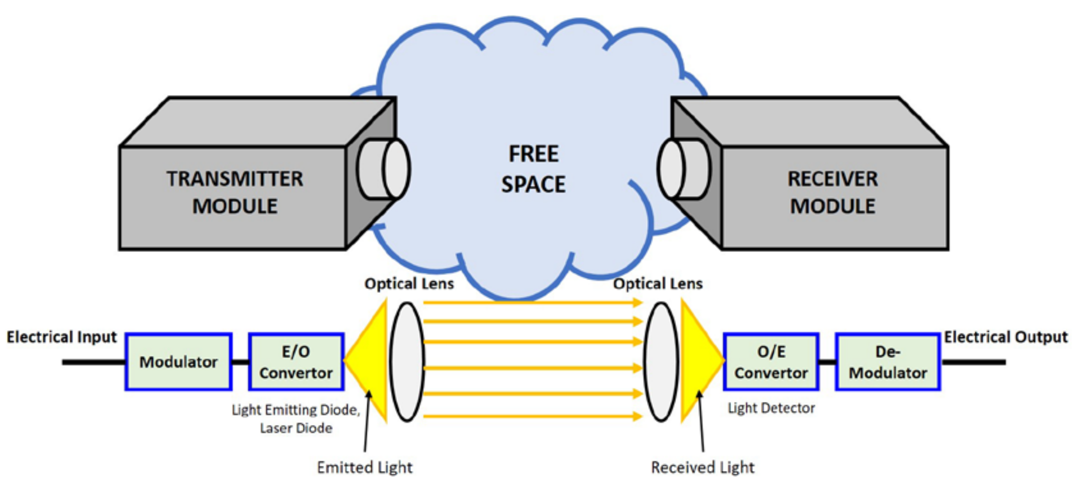

Figure 1. Diagram of a Basic Free Space Optical Communication System. Adapted from [1].

The transmitter module comprises a modulator connected to an electrical-to-optical convertor (such as light-emitting diodes or laser diodes). Through spontaneous emission, it emits photons with wavelengths corresponding to the energy difference between the energy states when an atom drops from a higher energy level to a lower energy level. The photons are focused to optical lenses before transmission into the air medium. The primary purpose for these lenses is to shape the light beam propagation and to create a collimated ray to minimize light divergence.

The receiver module comprises receiving optical lenses, which capture the transmitted light. These lenses focus the photons to the light detector (an optical-to-electrical convertor). After passing the de-modulator, the electrical output will contain the transmitted data.

It can be observed that the optical communication is a directed line-of-sight (LOS) communication where it is important to have the least physical obstruction between the two modules to ensure optimized transmission of data. Furthermore, it is noted that a singular module may have both transmitting and receiving capabilities within itself.

B. LINK EQUATION

The FSO Link Equation shows the relationship in which received power is directly proportional to the aperture area of the power transmitted and inversely proportional to the link range and beam divergence angle [3]. It also includes an exponential portion relating to atmospheric attenuation and beam divergence angle. It can be observed that with all other factors held constant, any change in atmospheric attenuation will cause the greatest impact to the link equation.

$$P_{received} = P_{transmitted} \times \frac{A_{receiver}}{(d \times R)^2} \times e^{-aR}$$

where

P	= Power (dB)
A	= Aperture (m)
d	= Beam divergence angle (mrad)
R	= Link range
a	= Atmospheric attenuation (dB/km)

C. ADVANTAGES

The three key advantages of FSO communications systems are their high bandwidth, immunity to electromagnetic interference and high level of security.

1. Bandwidth

Bandwidth, often used to describe network speed, relates to the amount of data sent over a specific connection in a given amount of time [4]. FSO communication systems operate at shorter wavelengths, which directly relates to it operating at higher frequency as compared to the other wireless communication devices that operate in the RF spectrum. Hence, FSO communications systems are able to achieve a higher data rate, depending on the propagation characteristics of the link.

High bandwidth is the main advantage for selecting FSO as a communication technique. With the ability to transmit at a higher data rate, it becomes a potential candidate to address the high demand for bandwidth in the networking industry. Indeed, directed optics (fiber) rates have been demonstrated above 1 Tbps [5]. While such rates are not to be expected in an FSO system due to atmospheric interference, as described in the next section, the potential capacity of these systems holds promise for tactical operators nonetheless.

2. Immunity to Electromagnetic Interference

Electromagnetic Interference (EMI), also known as Radio Frequency Interference (RFI), is the effect of electromagnetic disturbance affecting the performance of a device, transmission channel, or electronics systems [6]. For communication systems, it can introduce noise in the transmission and degrade the communication channel. Its effects can be as bad as damaging the electronics circuits of the systems. Communication systems operating in the RF spectrum are particularly vulnerable to EMI.

By contrast, FSO technology rides on optical communication, and it does not operate in the RF spectrum. Therefore, it is immune to EMI and its effects. This is a great advantage for communication systems.

3. Security

Security is a frequent topic of interest related to communication systems; for military communication systems, it is a principal concern.

In contrast to RF wireless communications, which broadcast their signal in a wide area, FSO communication is a directed, narrow beam [7]. In order to intercept the signal, one needs to be in the direct path of the beam, which makes the probability of interception rather low. In the event one is in the path of the directional beam, a decrease in power received will be observed, and the transmitting module may halt the transmission to avoid data interception. Another possible means of data interception is when one is behind the receiver. Additional security measures can be implemented to block the signal behind the receiver using a blocking shield [7].

Furthermore, since the beam is invisible to the naked eye and cannot be detected with an RF meter or spectrum analyzer, it makes the probability of detection very low as well [1]. Lastly, additional security can always be deployed similar to the measures used for all other types of communication, such as data encryption prior to signal encoding and transmission.

D. CHALLENGES

Similar to all communications systems, FSO communications systems also face challenges and have their limitations. Three of them are mentioned in this section.

1. Line-of-Sight Communication

As mentioned in the previous section, FSO communication is highly dependent on LOS between the sender and the receiver. Furthermore, LOS must be maintained throughout the data transmission period. Hence, availability is crucial for an FSO communication network.

This may be challenging as the environment is usually populated with physical obstructions such as vegetation, buildings, or even animals. It may not be easy to find a clear LOS for ground-to-ground, ground-to-air, and air-to-ground communication. However, it is definitely advantageous to employ FSO communication systems for air-to-air and sea-related communication.

2. Atmospheric Effects

FSO communication is greatly affected by nature. As observed from the FSO link equation given earlier, atmospheric attenuation is a contributing factor for power received by the receiver module.

Some of the atmospheric effects include absorption, scattering, and scintillation. Absorption occurs when molecular absorbers (gases) and/or aerosol absorbers (such as dust, smoke, and other forms of pollution) cause the level of optical energy to be decreased [8]. Absorption has an effect on the strength of the FSO communication beam [2].

Scattering occurs when the optical energy is dispersed, resulting in a directional redistribution of energy. There are three main types of scattering: (1) Rayleigh scattering (caused by gases), (2) Mie scattering (caused by aerosol, fog), and (3) Non-selective scattering (caused by snow, rain) [8]. Of these, scattering due to fog causes the highest atmospheric attenuation. Figure 2 shows atmospheric attenuation caused by scattering due to fog and haze (Mie scattering).

Description	Visual range	Loss (dB km^{-1})
Dense fog	40–70 m	250–143
Thick fog	70–250 m	143–40
Moderate fog	250–500 m	40–20
Light fog	500–1000 m	20–9.3
Thin fog	1–2 km	9.3–4.0
Haze	2–4 km	4.0–1.6
Light haze	4–10 km	1.6–0.5
Clear	10–25 km	0.5–0.1
Very clear	25–50 km	0.1–0.04
Extremely clear	50–150 km	0.04–0.005

Figure 2. Atmospheric Attenuation Due to Scattering. Source: [9].

Scintillation is an effect of heat that creates temperature variations in the air pockets along the path of an optical link [2]. This causes fluctuations in the optical beam, resulting in variation of energy received or irregular distribution of energy over the beam diameter. Heat haze, twinkling (similar to starlight), and mirages are examples of scintillation. This effect is most prominent during ground-to-ground communication, especially over concrete surfaces where heat from the sun is almost fully reflected.

3. Safety

FSO communication systems operate in the wavelength of 780–1,600 nm. According to the EM Spectrum chart shown in Figure 3, this range falls in the Near Infrared (700–1,400 nm) and the Far Infrared (beyond 1,400 nm) regions. The portion that falls within the Near Infrared region is considered as the retinal hazard region [10].

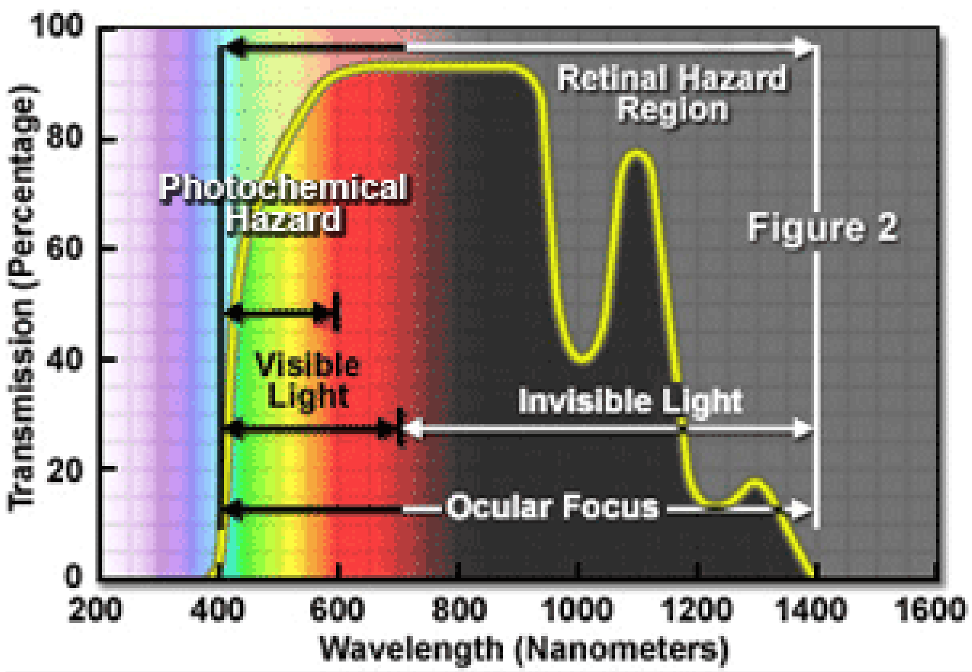

Figure 3. Retinal Hazard Region. Source: [11].

Figure 4 shows that Far Infrared rays will be blocked by the eye's cornea, but Near Infrared rays will penetrate through the cornea, iris, and pupil and get focused by the lens, concentrating all the power of the ray on the retina of the eye.

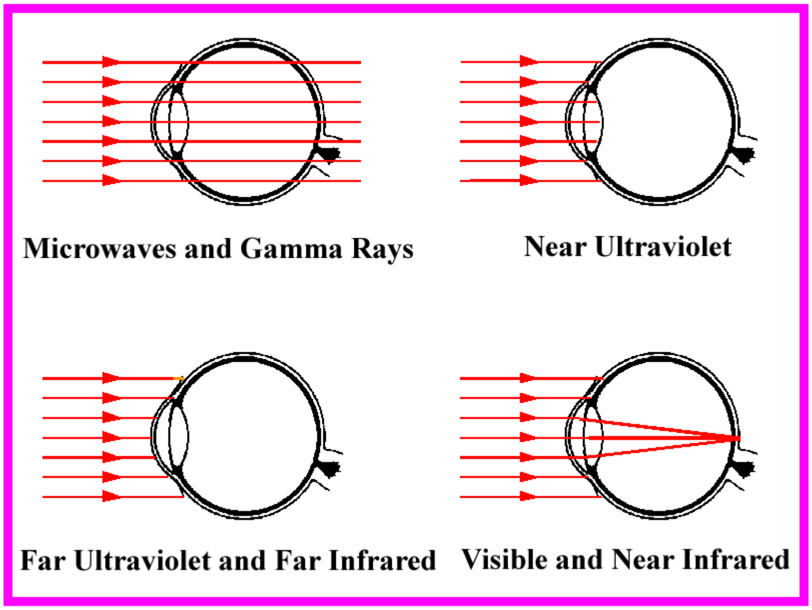

Figure 4. Illustration of Effect of Different Rays. Source: [10].

Since laser affects the eye, especially for Near Infrared wavelength where all the power is concentrated to the retina, a laser classification is set to determine the safe use of different classes of lasers. This laser classification and standard was concluded by the American National Standards Institute (ANSI) Z136 committee, as published in ANSI Z136.1 Standard [12].

Figure 5 shows the classification with description of the effects with respect to each class of laser.

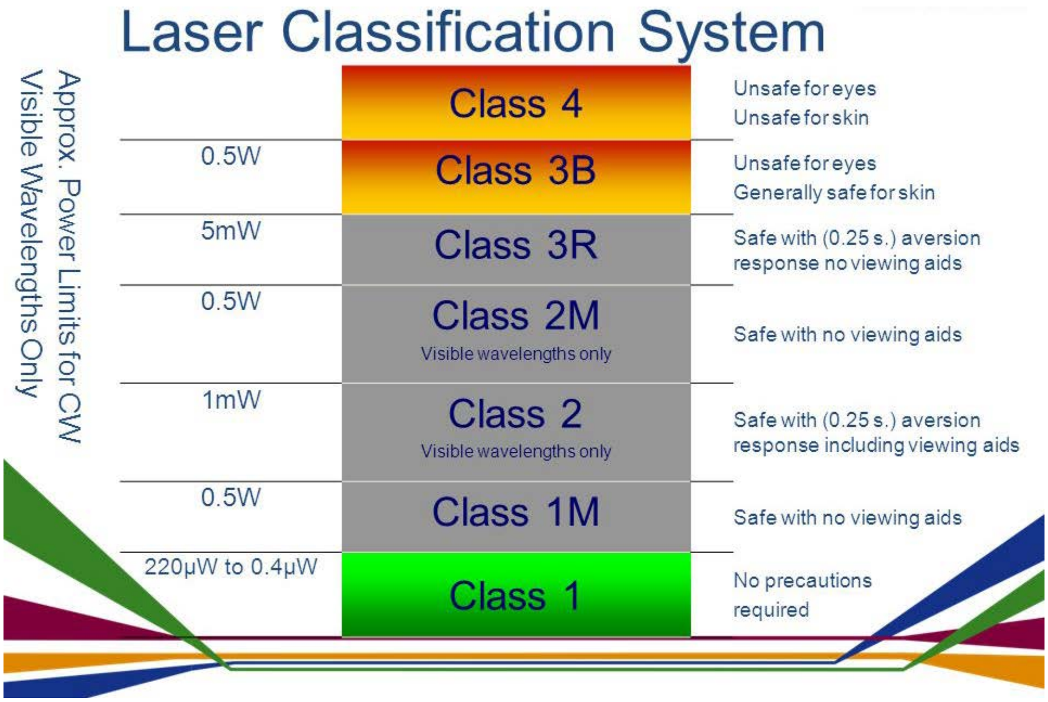

Figure 5. Laser Classification System. Source: [13].

Class 1 lasers are safe and require no precaution because they are usually operating in an enclosure, such as a laser printer or CD ROM player [14]. Class 1M lasers emit higher power, hence it is not safe with viewing aids as the power will be focused when it reaches the eye. Classes 2 and 2M are solely for lasers at visible wavelengths. An example for Class 2 laser is low power laser pointers [13]. Higher class of lasers are usually used for laser cutting purposes where high and concentrated power from the laser burn and cut the material.

FSO communications systems are designed to be operating in the eye-safe wavelength and slightly higher in power to transmit over a certain range. Therefore, they usually falls into a Class 1M laser classification.

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III. EXPERIMENT PREPARATION

This chapter documents the preparation process to conduct a laser-related communication experiment. The chapter introduces the product tested for this thesis followed by the proposed process, and it describes the drafting of the experimentation plan used. The process also incorporates the required procedure for performing laser-related tests involving the United States Navy.

The following sections provide considerations on how the experimentation plan is designed and why certain actions are recommended. The experiments were conducted in Camp Roberts, California. It is a National Guard post and is ideal for the experiments as it offers the availability of range. Furthermore, it is a controlled area for both personnel and vehicles, further enhancing safety.

A. NEXUS FREE-SPACE OPTICAL COMMUNICATIONS SYSTEM

SA Photonics provided their NEXUS 3 Free-Space Optical Communication System (see Figure 6) for the experiment and data collection for this research. The datasheet for the NEXUS FOS communication system can be found in Appendix A at the end of this report.

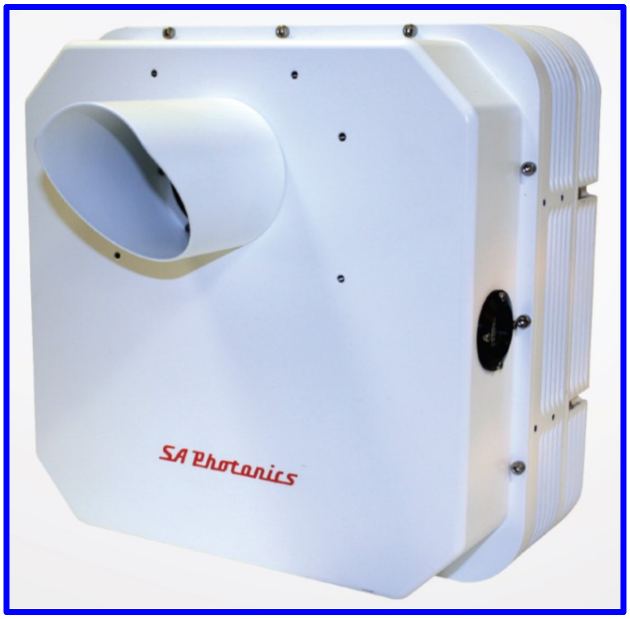


Figure 6. SA Photonics' Product, NEXUS 3 FSO Communications System. Source: [15].

The NEXUS FSO communication system is designed to be a 1 Gbps FSO communication system using a laser as the means of establishing a communication link. Its designed operating range is 1–30 km. For this thesis trial, NEXUS has been upgraded to support a 10 Gbps communication link and for a range of 2–10 km. Table 1 summarizes the parameters of the laser beam emitted by NEXUS.

Table 1. SA Photonics NEXUS Laser Parameters

SA PHOTONICS NEXUS LASER PARAMETERS	
Wavelength	1550 nm
Output Mode	Continuous Wave
Average Power	90 mW
Beam Profile	Circular
Beam Distribution	Gaussian
Beam Divergence	0.145 mrad
Beam Waist Diameter	1.5 cm
Beam Waist Range	0

Refer to Appendix B for more details of the NEXUS laser analysis.

The analysis of laser standards is governed in accordance with the American National Standard Institute's Standard for Safe Use of Laser (ANSI Z136.1). Using the parameters in Table 1, the NEXUS FSO communication system is a Class 1M Laser System [12].

B. PREPARATION PROCEDURE

For the laser communication experiment, the author adopts a systematic approach for the trial preparations. A flow diagram of the procedure is shown in Figure 7.

Figure 7. Flow Diagram of Preparation Procedure.

A preliminary experimentation plan is first drafted to include the objectives, scope, test setup and instructions. However, because the experiment involves laser communications that require safety clearance, the Operational Risk Management (ORM) process is introduced before finalizing the experimentation plan. After performing the required ORM steps, the author redesigns the test setup and instructions to include the recommendations from the assessment of the ORM.

The steps and considerations are established in the next few sections of this chapter.

C. PRELIMINARY EXPERIMENTATION PLAN

For most experiments, considerations will revolve within the preliminary plan. For laser-related experiments, the preliminary plan is drafted to facilitate the clearance for laser-related safety concerns.

1. Objectives

It is important to specify the objectives of the test clearly in order to set the direction and goals for the experiments. The primary objective is to test the network performance of the NEXUS FSO communication system over varying distances. There are two concerns associated with this objective. First, the experiment is to verify the system’s performance within the range of 2–5 km, as that is the distance over which the system had been previously tested by the vendor. Since Camp Roberts offers a controlled site with a possibly longer link range, a second concern relates to whether the system could perform over a longer range as it is of vast interest from a tactical operations perspective to investigate the system’s performance over longer distances.

Furthermore, the Joint Interagency Field Experiment (JIFX) also serves as a stepping stone for SA Photonics to extend their future testing in military contexts. They went through various rounds of laser safety reviews with the Navy in the process of clearing the NEXUS system to enable its use at JIFX, and as a result, certain standard operating procedures (SOP) and protocols were established. Following a successful demonstration of NEXUS capabilities and assuring that the experimentation team is able to adhere to the established SOPs will definitely present more opportunities for both SA Photonics and the military to jointly explore the capabilities of the system.

2. Scope

The scope effectively draws boundaries for the test. As the duration for the entire test is limited and considering that it takes significant time to locate ideal spots for LOS testing and to travel from one location to another, distances are not in regular increments. Furthermore, though there are many parameters that can be used to measure network performance, the scope of this test is limited to packet losses and sustained data rate.

3. Setup

The proposed setup for the required experiments and the list of items and their individual purposes are shown in Figure 8 and Table 2, respectively.

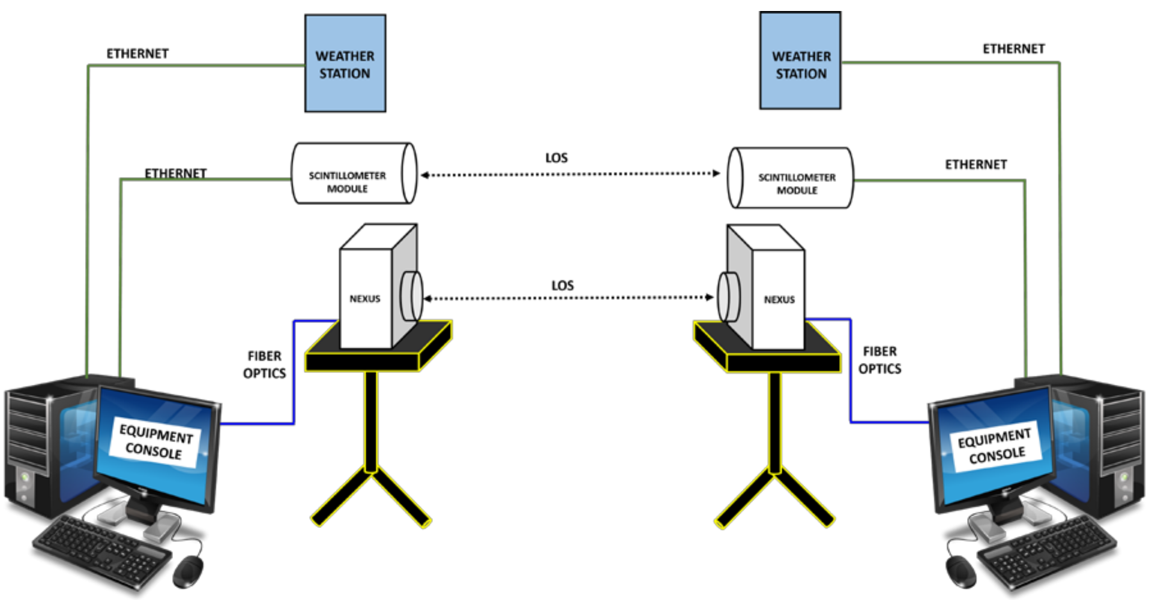


Figure 8. Proposed Setup for Experiments

Table 2. List of Items and Their Purposes

S/N	ITEM	DESCRIPTION
1	NEXUS	- FSO communication system being explored - Capable of both transmitting and receiving data - Connected to the equipment console using fiber optics cable
2	Scintillometer Module	- Measures atmospheric scintillation - Connected to the equipment console using an Ethernet cable
3	Weather Station	- Measures atmospheric information - Connected to the equipment console using an Ethernet cable
4	Equipment Console	- Set parameters of NEXUS - Attached to an external Ethernet tester - Monitors and logs parameters and measurements of NEXUS, the scintillometer module, and weather station

4. Procedural Instructions

After setting up the equipment at the designated sites according to the setup shown in Figure 8, the first step is to align the NEXUS communications system on both terminals, using a rifle scope, to ensure LOS. The scintillometer has to be aligned in the same manner. These steps are performed prior to powering up the systems.

Before powering up the system on both terminals, it is important to ensure that there are no physical obstructions in between both terminals. This is done to maintain consistency in the data collection. Additionally, care should also be taken to ensure that no personnel are in the LOS of both terminals to mitigate the risk of eye damage.

The final step is to ensure communication (via radio or other means) between the operators on both terminals is maintained consistently.

D. OPERATIONAL RISK MANAGEMENT

In accordance with OPNAV INSTRUCTION 5100.27B and NAVPGSCOL INSTRUCTION 5100.27A, Operational Risk Management, as per enclosed in OPNAV INSTRUCTION 3500.39C, has to be performed prior to laser-related experiments being conducted that involve Navy and NPS personnel.

The ORM framework follows a five-step deliberate and in-depth process: (1) Identify Hazards, (2) Assess Risks, (3) Make Risk Decisions, (4) Implement Controls, and (5) Supervision. A risk analysis (refer to Appendix C) for the NEXUS communications system was done according to the ORM by the NPS Laser Safety Officer in conjunction with the Department of the Navy Laser Safety Review Board.

1. Identify Hazards

The first step of ORM is the identification of potential hazards that may compromise safety. To provide a more complete list of these potential hazards, one has to have a good understanding of the system being used, how it is operated, and also the tests the system is required to go through prior to use. In the author's opinion, this step bears close relationship with the test plan. The latter is used to determine the former; the former is able to influence the latter.

The author categorized the hazards into laser specific and non-laser specific hazards.

a. Laser-Specific Risks

It was shown earlier that the NEXUS communications system is a Class 1M Laser System. Therefore, the first hazard identified is "eye damage from viewing aids" [13]. Next, owing to the fact that there is a possibility that the output energy from the laser goes beyond the stated limit, the eye may still be damaged from direct intra-beam viewing, which forms the second identified hazard.

b. Non-Laser Specific Risks

For non-laser specific hazards to be identified, considerations have to be placed in the setup and the equipment involved. For instance, consider whether there will be excessive heat or possible chemical exposure when the equipment operates. After careful review of the test setup and the equipment required, no hazard has been identified in this category.

2. Assess Risks

According to the ORM, risk is assessed based on severity of the risk and probability of it happening. Table 3 is the Risk Assessment Matrix provided by the ORM.

Table 3. Risk Assessment Matrix for NEXUS before Controls Implementation. Source: [16].

Risk Assessment Matrix		**PROBABILITY**			
		Frequency of Occurrence Over Time			
		A Likely	B Probable	C May	D Unlikely
I	Loss of Mission Capability, Unit Readiness or Asset; Death	1	1	2	3
II	Significantly Degraded Mission Capability or Unit Readiness; Severe Injury or Damage	1	2	3	4
III	Degraded Mission Capability or Unit Readiness; Minor injury or Damage	2	3	4	5
IV	Little or No Impact to Mission Capability or Unit Readiness; Minimal Injury or Damage.	3	4	5	5
Risk Assessment Codes **1** – Critical **2** – Serious **3** – Moderate **4** – Minor **5** – Negligible					

Risk Assessment for personnel is indicated by the white circle.

Risk Assessment for equipment is indicated by the red circle.

With reference to the assessment made, a person may burn his cornea in the event of a direct intra-beam viewing, making the severity a Category II—Severe Injury, and with insufficient implementation of controls, the probability is likely a Sub-Category A injury. Hence, it corresponds to Risk Assessment Code 1, which is Critical Risk. For equipment, since no hazard was identified, it falls into Risk Assessment Code 5, which is Negligible.

3. Risk Decisions

This step aims to make risk decisions by identifying available options to mitigate the identified risks and also to consider the effects of each option identified. Table 4 summarizes the analysis of Step 3 for NEXUS.

Table 4. Summary of Control Options and Their Effects. Source: [16].

S/N	CONTROL OPTIONS	CONTROL EFFECTS
1	Restrict emitted power	Reduces the severity and probability of eye damage
2	Reduce emitting power to minimum required	Reduces range of viewing aids hazard zone
3	Prohibit viewing aids from laser beam viewing aids hazard zone	Eliminates the probability of eye damage due to viewing aids
4	Prohibit viewing aids from laser beam viewing aids hazard zone when laser is on	Reduces the probability of eye damage due to viewing aids
5	Minimize access to beam path by choosing an overhead path with a large terrain clearance	Reduces the probability that people are inbetween the LOS of the beam
6	Prohibit operations if scintillation effects are present	Reduces the probability of eye damage
7	Capture beam spot at terminal	Reduces the risk of events occuring due to scintillation

It was further assessed that at a distance greater than 1.3 km, the beam energy gathered by viewing aids will not be sufficient to exceed the threshold at which it is harmful to a person’s eye.

The final risk decision was made to apply Controls 1, 2, 4, and 5 for the JIFX experiments involving the NEXUS communications system. Considerations included that the experiment is conducted within Camp Roberts (controlled access for both land and air space); hence, the various controls will be sufficient and effective from a safety standpoint.

4. Implement Controls

This step recommends implementation of the controls to mitigate the identified risks. Table 5 provides the list of available control options and their corresponding implementations.

Table 5. Available Control Options and Their Corresponding Implementations. Source: [16].

S/N	CONTROL OPTIONS	IMPLEMENTATIONS
1	Restrict emitted power	- Restrict power output by installing attenuator - Apply a screen between operators and NEXUS
2	Reduce emitting power to minimum required	- Include in procedural instructions to measure emitted power before beginning the experiment and monitor the power level during laser operations
3	Prohibit viewing aids from laser beam viewing aids hazard zone	NIL
4	Prohibit viewing aids from laser beam viewing aids hazard zone when laser is on	- Include in procedural instructions to prohibit operators from the use of viewing aids, such as binoculars, after the systems are powered on
5	Minimize access to beam path by choosing an overhead path with a large terrain clearance	- Site selection to ensure at least a 15' clearance over all obstacles - Site selection to ensure access is limited
6	Prohibit operations if scintillation effects are present	NIL
7	Capture beam spot at terminal	NIL

Furthermore, terminals are placed at least 1.3 km apart. This is for the safety of the operators to cover the possibility that they are within 1.3 km and using a viewing aid in the viewing aids hazard zone. Ensuring that the testing range is more than 1.3 km eliminates this risk totally.

5. Supervise

Supervision includes ensuring that the implemented controls are executed as planned, monitoring the situation on-site, and adjusting the controls accordingly. Furthermore, this step also reviews whether there is any new hazard that should have been identified and, if so, the process begins from step 1 again.

6. Risk Management Summary

After a few iterations of the five-step process and finalizing the required mitigating actions, the Risk Assessment Matrix is reviewed again. The Risk Assessment for equipment remains unchanged at "5." The Risk Assessment for personnel has been brought to Risk Assessment Code 5 with its reduced severity and reduced probability, as shown in Table 6. Apart from mitigating the risk factor to its minimum, the process also ensures participants make considerations for operational requirements.

Table 6. Risk Assessment Matrix for NEXUS after Controls Implementation. Source: [16].

Risk Assessment Matrix		PROBABILITY Frequency of Occurrence Over Time			
		A Likely	B Probable	C May	D Unlikely
I	Loss of Mission Capability, Unit Readiness or Asset; Death	1	1	2	3
II	Significantly Degraded Mission Capability or Unit Readiness; Severe Injury or Damage	1	2	3	4
III	Degraded Mission Capability or Unit Readiness; Minor injury or Damage	2	3	4	5
IV	Little or No Impact to Mission Capability or Unit Readiness; Minimal Injury or Damage.	3	4	5	5

Risk Assessment Codes
1 – Critical **2** – Serious **3** – Moderate **4** – Minor **5** – Negligible

E. CONSTRUCTING FINAL EXPERIMENTATION PLAN

The final part for the experiment preparation is development of the experiment plan. Figure 9 shows the improved experimentation setup with the inclusion of the screen, acting as backstop, to ensure that operators are well protected from any beam spillover.

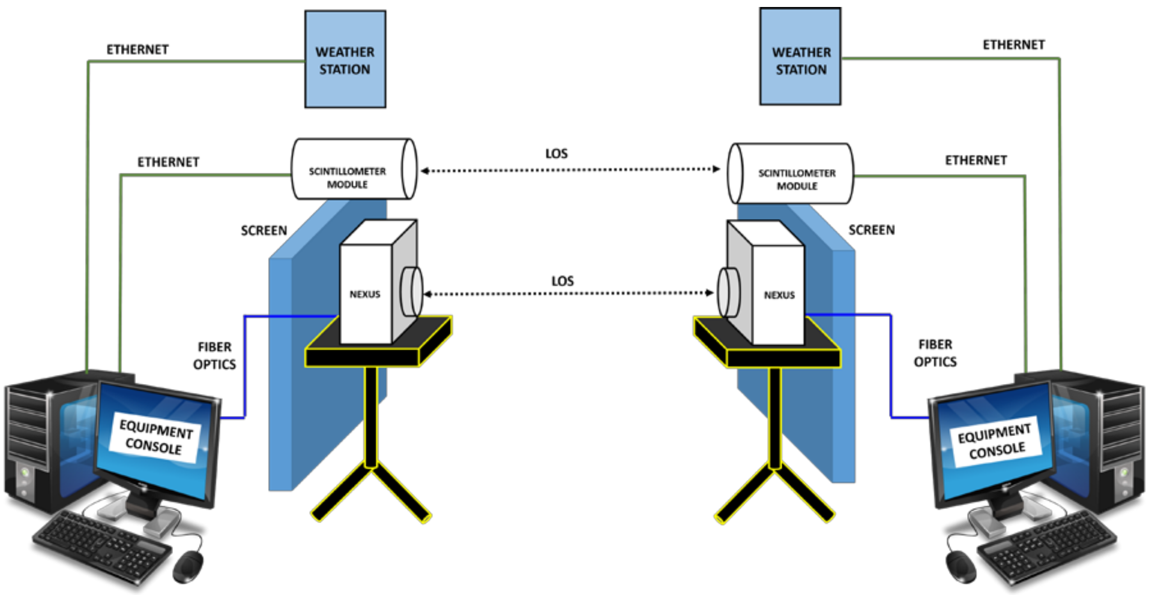


Figure 9. Final Setup for Experiments

Furthermore, additional steps and precautions are added to the instructions. These include adding an output power control process (prior to start of test) in which an external power meter is used to countercheck that the emitted power is within the stated limitation. Further, an additional precaution regarding the prohibition of the use of viewing aids when the laser beam is on was included. The implemented experimentation plan is attached in Appendix D.

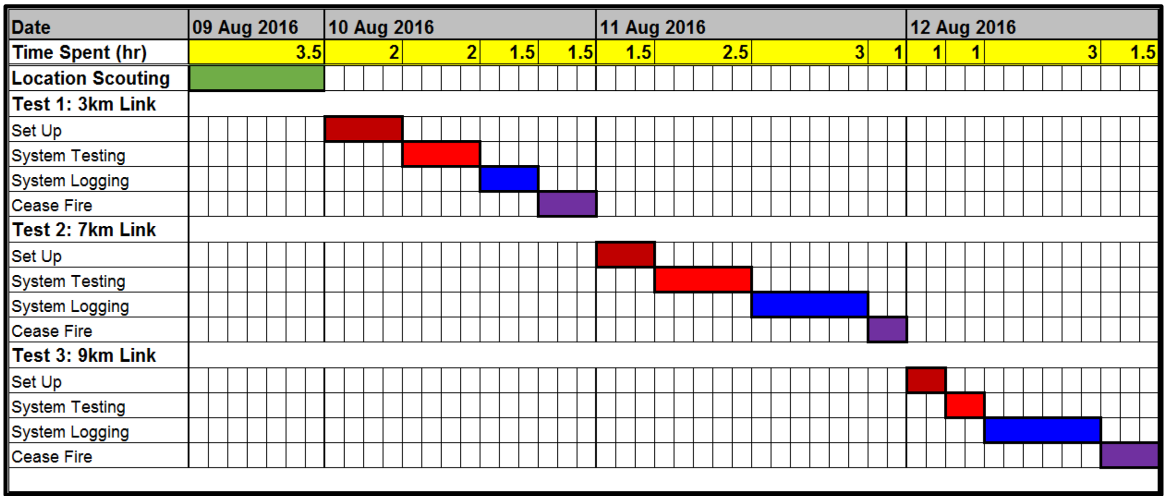
IV. EXPERIMENTATION AND ANALYSIS

This chapter provides a documentation of the experiments conducted during JIFX for this thesis. Over the span of 25 hours, several locations were identified for the required experiments, three different link ranges of laser communication were established, and seven hours of positive data were logged for analysis. This chapter also provides the consolidation of collected data and presents an analysis according to the experimental results.

A. TIMELINE

Table 7 shows the effort spent in the various areas to facilitate the successful completion of the thesis trial. Establishing LOS between the two terminals is critical; hence, approximately 15 percent of the time was spent scouting potential sites for the experiment. However, due to limitations in time, only three ranges were tested. With reference to the table, it can be observed that more time was used in the first setup, and it subsequently became faster as the team became more familiar with the setup, radio communication, and the SOP determined by the ORM. Finally, more time was spent in the first system testing to ensure the system is operating as intended and when the NEXUS system first established a 7 km link.

Table 7. Timeline of NEXUS Experiments



B. RECONNAISSANCE

As a first time participant in JIFX, reconnaissance was performed a day prior to the start of the actual experiment. Apart from meeting the NPS Field Experiment Team to gain understanding on the proceedings with respect to conducting the experiment, scouting of suitable locations was done.

As this technology requires LOS between the two communicating modules, it is critical to be able to identify locations that provide unobscured LOS. Furthermore, the objective of the experiments is to understand the performance of the product across varying link ranges. Hence, various spots are required to be identified.

During reconnaissance, the author managed to identify ten potential spots for the systems to be positioned. A mesh of the locations provides a set of varying distances that satisfies the test objectives. Table 8 shows the coordinates of the identified locations and the link ranges which they are targeted to achieve.

Table 8. Coordinates of Identified Locations and Their Respective LOS Ranges

S/N	LOCATION 1	LOCATION 2	LOS RANGE
1	35° 42' 16.9" N, 120° 48' 19.1" W	35° 42' 57.32" N, 120° 48' 40.89" W	1.51 km
2	35° 42' 16.9" N, 120° 48' 19.1" W	35° 43' 25.08" N, 120° 47' 30.62" W	2.43 km
3	35° 44' 26.29" N, 120° 47' 09.81" W	35° 45' 53.4" N, 120° 46' 11.8" W	3.06 km
4	35° 42' 16.9" N, 120° 48' 19.1" W	35° 43' 28.78" N, 120° 46' 32.11" W	3.50 km
5	35° 42' 16.9" N, 120° 48' 19.1" W	35° 44' 03.05" N, 120° 46' 54.59" W	3.90 km
6	35° 42' 16.9" N, 120° 48' 19.1" W	35° 44' 23.91" N, 120° 47' 15.41" W	4.23 km
7	35° 42' 16.9" N, 120° 48' 19.1" W	35° 45' 53.4" N, 120° 46' 11.8" W	7.47 km
8	35° 42' 16.9" N, 120° 48' 19.1" W	35° 46' 35.2" N, 120° 44' 59.1" W	9.40 km

The main strategy was to set a permanent pivot point at the peak of Nacimiento Hill while a remote station shifts to various positions to beam to that pivot point. Next, the author sought clearance with the NPS Laser Safety Officer to ensure that laser communications can be established between each pair of identified spots. The highlighted rows are the locations used during JIFX.

C. EXPERIMENTS AND RESULTS

The conducted experiments and their results are described in this part of the chapter. The NEXUS FSO communications systems transmit at a 10 Gbps data stream that carries Ethernet payload (packed with current frames and retransmitted frames and idle frames to fill up the space).

1. Experiment 1: 3 km Link

Figure 10 shows the locations of the two terminals for this first experiment, and Figure 11 shows the elevation profile between them. It can be observed that the terminals are not obstructed by terrain and the estimated minimum overhead clearance is about 10 meters, which is above the safety requirement identified by the SOP. Experiment 1 was conducted between 3:00 p.m. and 4:30 p.m on August 10, 2016. It was a clear sky with little wind. The day started at 87 Fahrenheit and ended at 88 Fahrenheit.

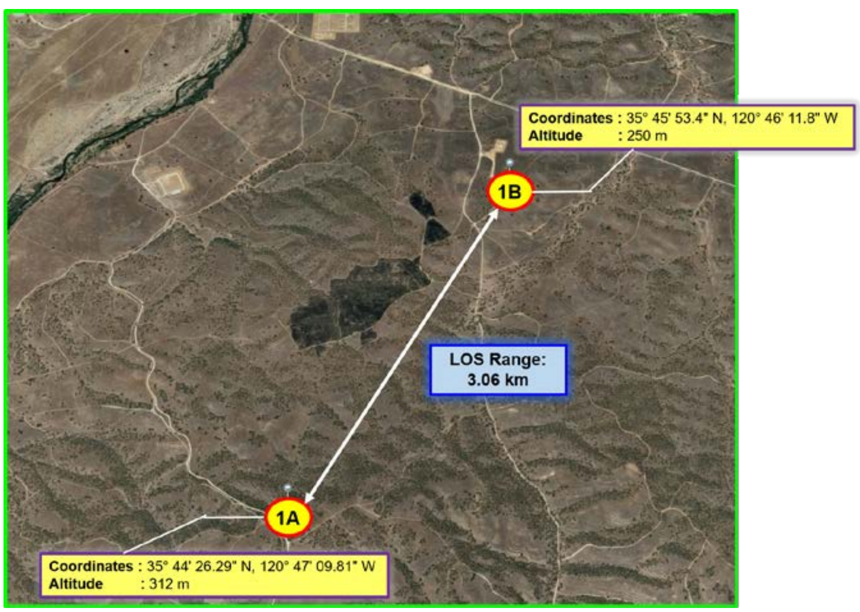


Figure 10. Locations for Experiment 1

Figure 11. Elevation Profile between the Two Terminals for Experiment 1

a. Results at Location 1A

The Ethernet tester was configured to send and receive a 7.315 Gbps Ethernet payload from Location 1A. Figure 12, 13 and 14 present graphs depicting the received data rate corresponding to the transmission rate, the percentage of frame loss, and power received, respectively. Table 9 summarizes the mean and standard deviation of the performance parameters.

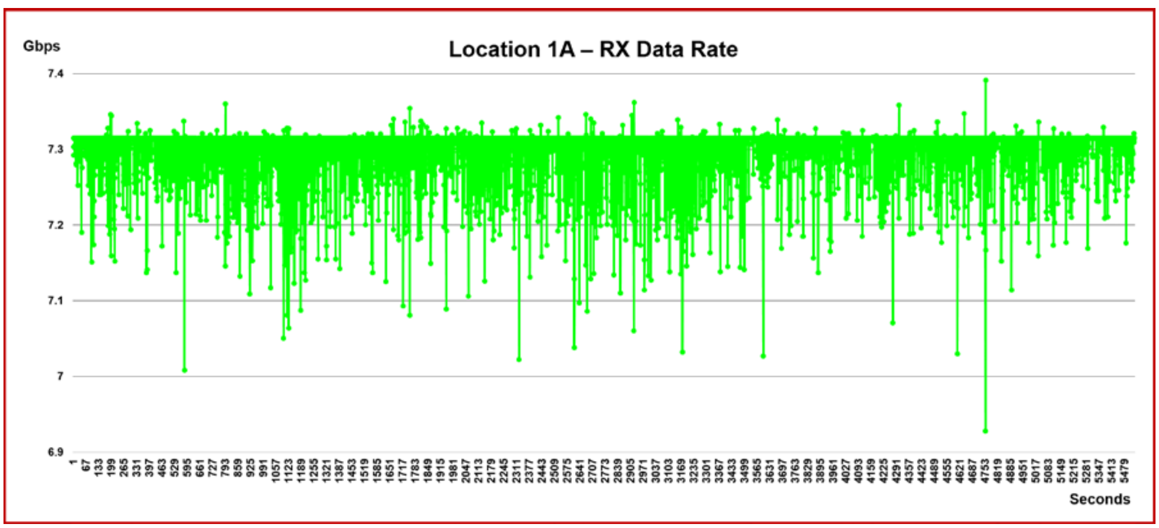


Figure 12. Received Data Rate at Location 1A

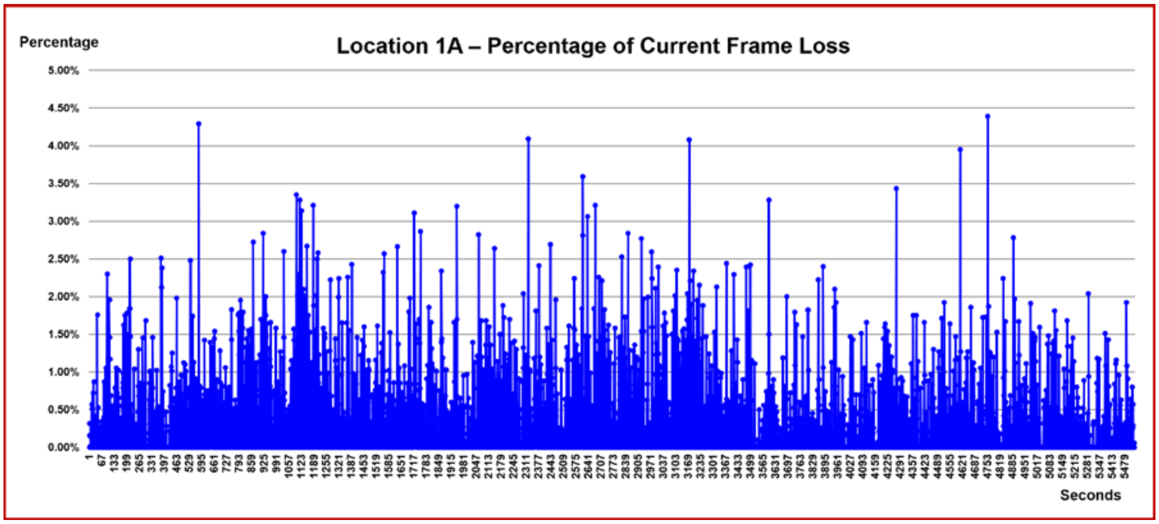


Figure 13. Percentage of Frame Loss at Location 1A

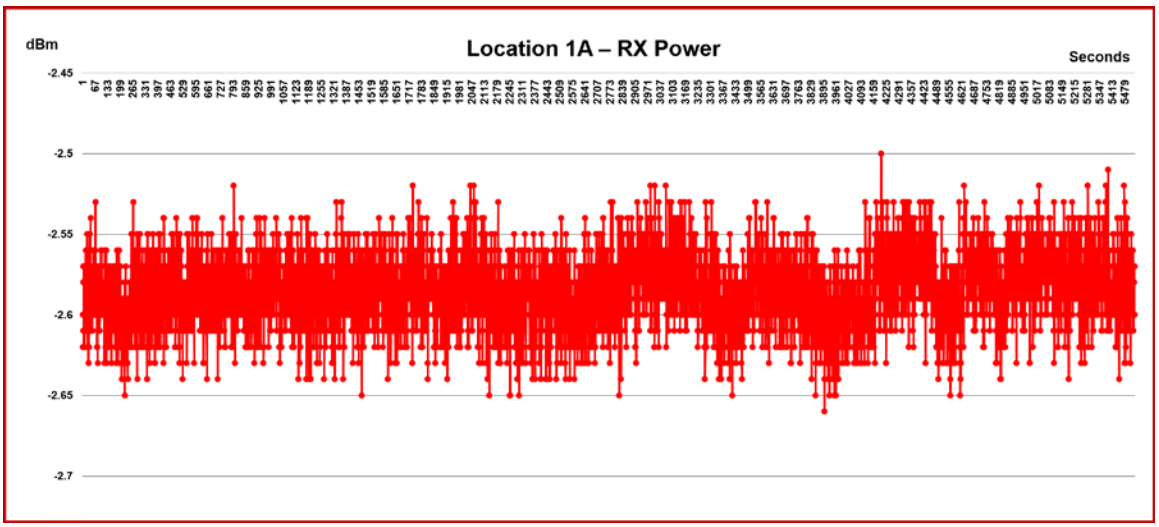


Figure 14. Received Power at Location 1A

Table 9. Mean and Standard Deviation of Performance Parameters at Location 1A

	Mean	**Standard Deviation**
Received Data Rate (Gbps)	7.235	0.03637
Percentage of Frame Loss (%)	0.28	0.00495
Received Power (dBm)	-2.585	0.0223

From Table 9, the values computed for standard deviation indicate that the spread of data is reasonably low.

It can be observed from Figure 12 that the received data rate ranges between 6.93 and 7.3 Gbps. The percentage of frame loss is also an indication of the re-transmission rate. It can be observed from Figure 13 that it is below 4.5%. Furthermore, a decrease in received data rate coincided in an increase in percentage of current frame loss, as expected.

From Figure 14, it can be observed that the received power ranges between -2.5 to -2.66 dBm. There is no relationship between the varying received power as compared to both the received data rate and the percentage of current frame loss. However, it can be deduced that the system is able to perform effectively when the received power is above -2.66 dBm (about 0.54 mW).

b. Results at Location 1B

The Ethernet tester was configured to send and receive a 7.315 Gbps Ethernet payload from Location 1B. Figures 15, 16, and 17 show the graphs representing the received data rate, the percentage of frame loss, and received power, respectively. Table 10 summarizes the mean and standard deviation of the performance parameters.

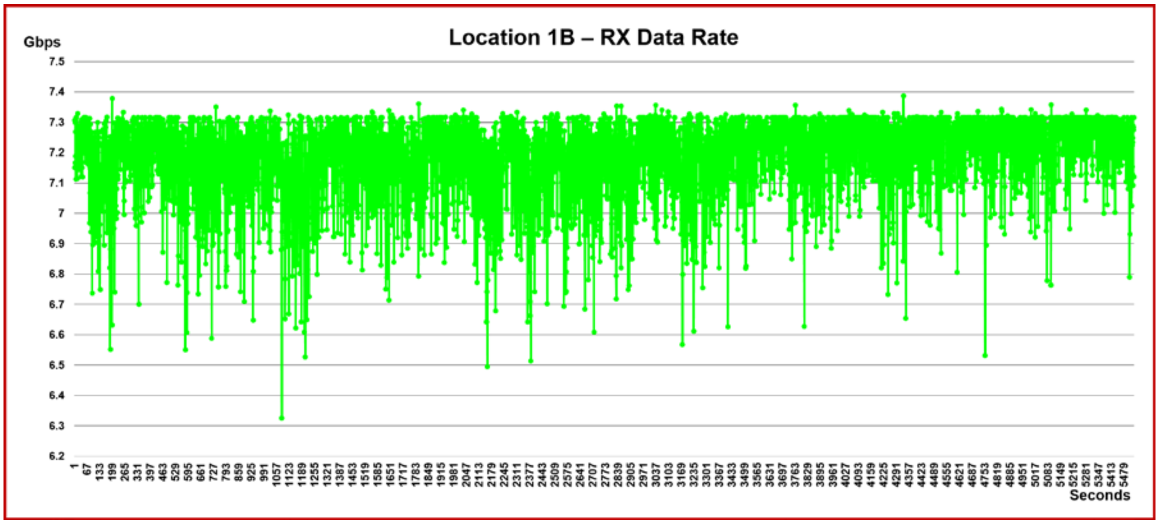


Figure 15. Received Data Rate at Location 1B

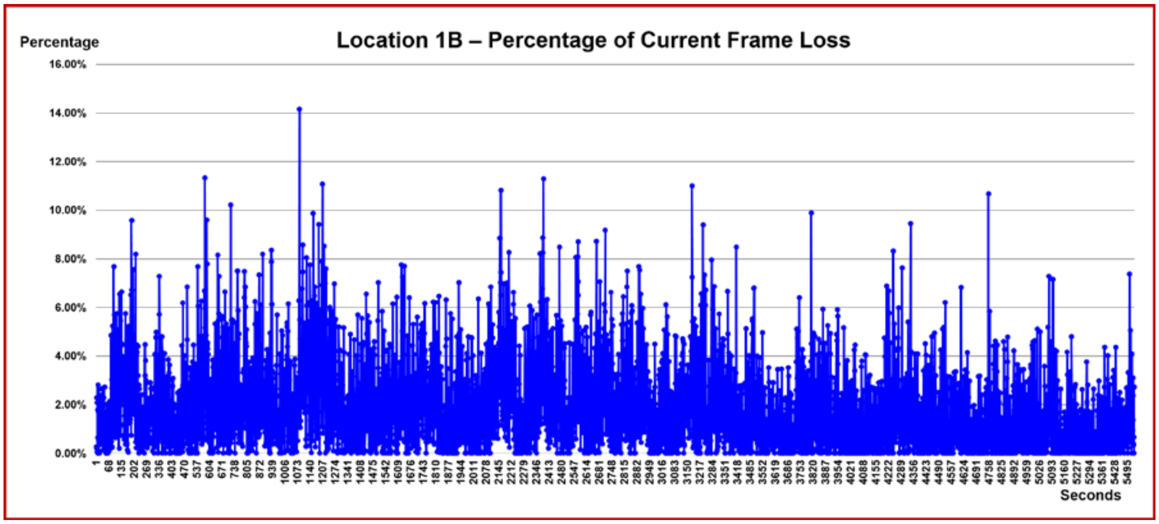


Figure 16. Percentage of Frame Loss at Location 1B

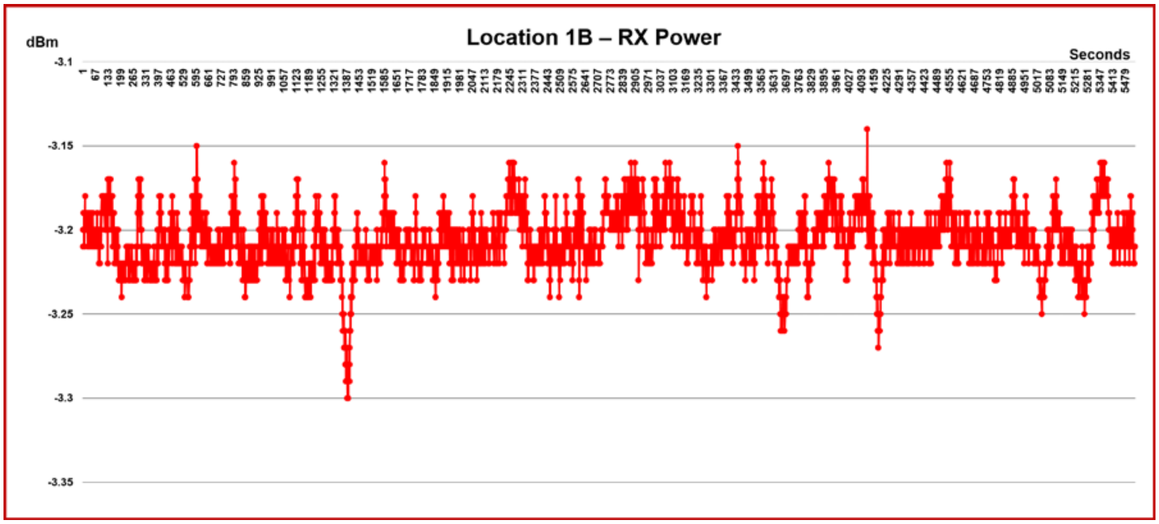


Figure 17. Received Power at Location 1B

Table 10. Mean and Standard Deviation of Performance Parameters at Location 1B

	Mean	Standard Deviation
Received Data Rate (Gbps)	7.184	0.12441
Percentage of Frame Loss (%)	1.83	0.01695
Received Power (dBm)	-3.206	0.01671

From Table 10, the values computed for standard deviation showed that the spread of data is reasonably low, though the consistency of the received data rate for this link, as indicated by the standard deviation, was less than that of the first link.

It can be observed from Figure 15 that the received data rate ranges between 6.3 and 7.3 Gbps. The mean of the percentage frame loss is 1.83 percent, which indicates that the re-transmission rate is good. It can be observed that the spike of 14 percent frames loss corresponds to the lowest received data rate at 6.3 Gbps.

The received power ranges from -3.14 to -3.3 dBm. Over this range of received power, the system is still able to perform efficiently. Comparing the results gathered at location 1A and location 1B, it can be observed that a decrease in power received resulted in a decrease in performance with respect to data rate and frame loss.

2. Experiment 2: 7 km Link

Figure 18 shows the locations of the two terminals for this experiment, and Figure 19 shows the elevation profile between them. It can be observed that the terminals are not obstructed by terrain, and the estimated minimum overhead clearance is about 5 meters, which is above the safety requirement. Experiment 2 was conducted between 12:30 p.m. and 3:30 p.m. on August 11, 2016. The experiment was conducted in a clear sky condition with little wind. The temperature ranges between 84 and 95 Fahrenheit.

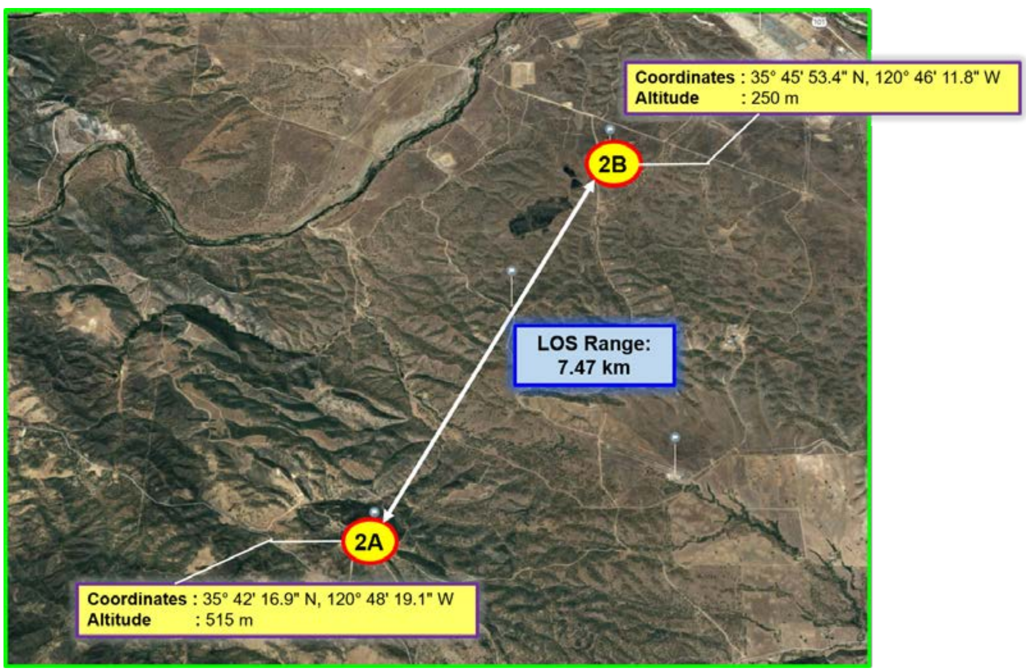


Figure 18. Locations for Experiment 2

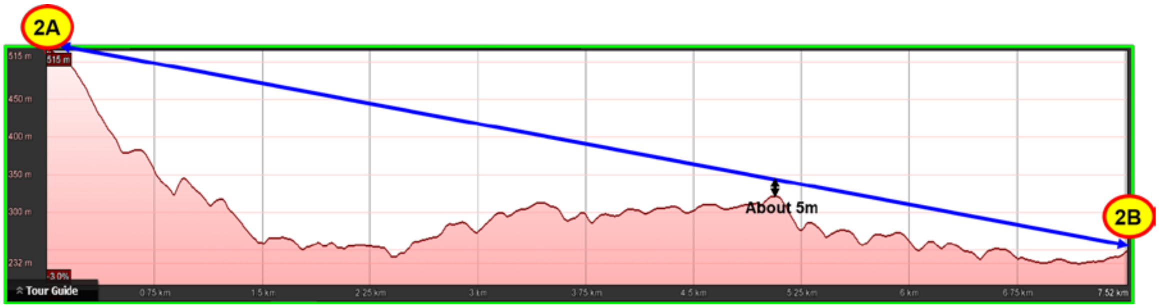


Figure 19. Elevation Profile between the Two Terminals for Experiment 2

a. Results at Location 2A

The Ethernet tester was configured to send and receive a 4.876 Gbps Ethernet payload from Location 2A. Figure 20, 21 and 22 shows the graphs representing the received data rate, the percentage of frame loss, and received power, respectively. Table 11 summarizes the mean and standard deviation of the performance parameters.

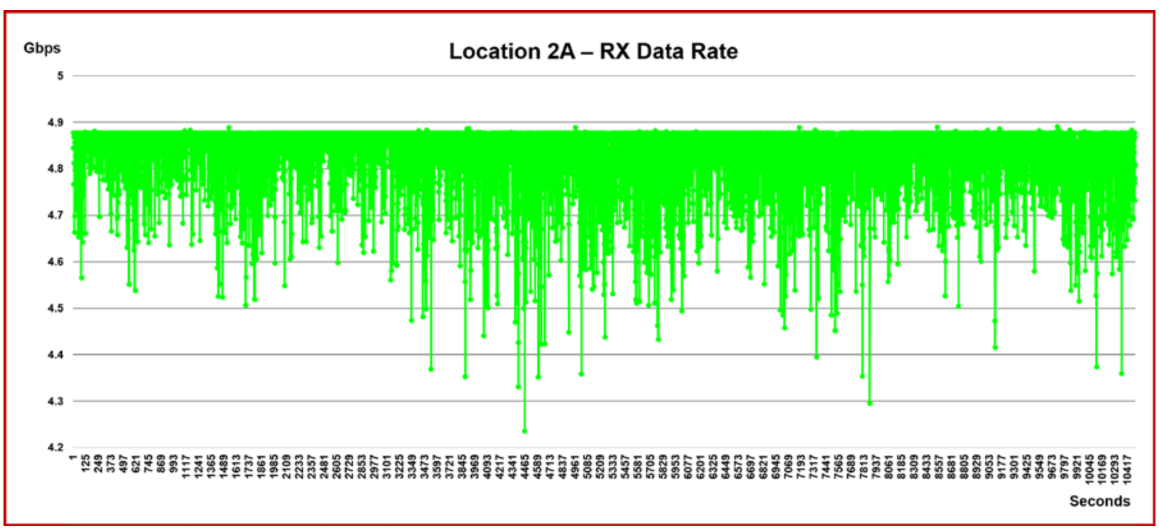


Figure 20. Received Data Rate at Location 2A

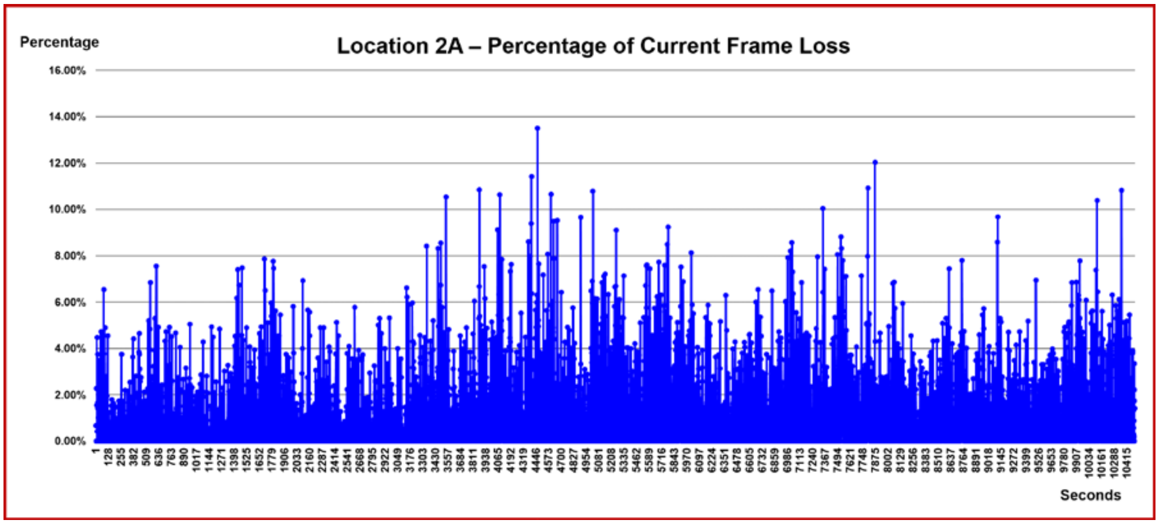


Figure 21. Percentage of Frame Loss at Location 2A

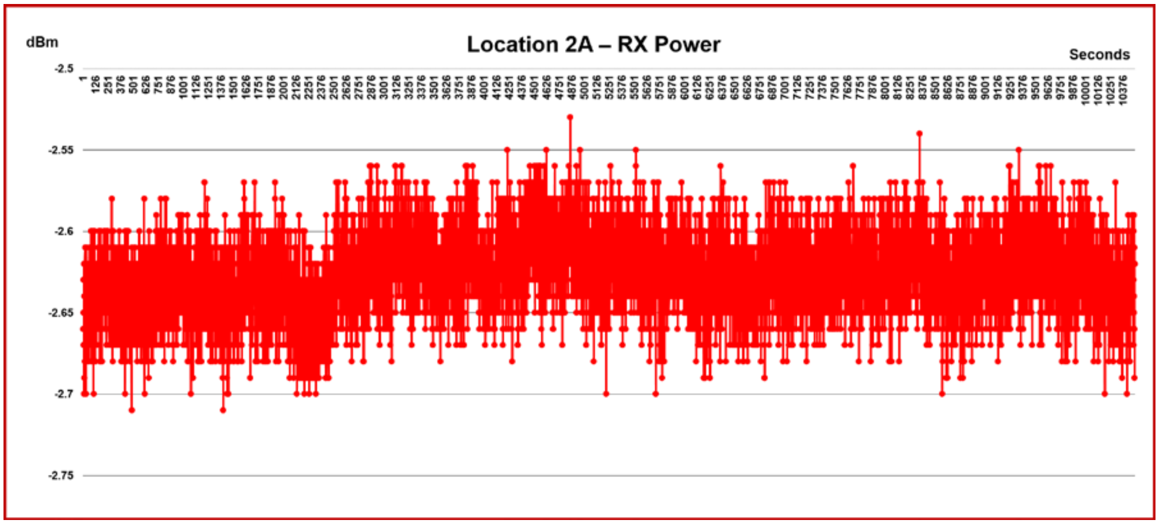


Figure 22. Received Power at Location 2A

Table 11. Mean and Standard Deviation of Performance Parameters at Location 2A

	Mean	Standard Deviation
Received Data Rate (Gbps)	4.83	0.06698
Percentage of Frame Loss (%)	0.93	0.01413
Received Power (dBm)	-2.63	0.02343

From Table 11, the values computed for standard deviation indicate the spread of data is reasonably low.

It can be observed from Figure 20 that the received data rate ranges between 4.2 and 4.87 Gbps. The percentage of frame loss appears to mirror the received data rate and is computed to have a mean below 1 percent.

From Figure 14, the received power ranges between -2.5 and -2.71 dBm. This result showed that NEXUS FSO communication system is able to perform effectively at 7.47 km when the received power is above -2.71 dBm (about 0.5 mW).

b. Results at Location 2B

The Ethernet tester was configured to send and receive a 4.876 Gbps Ethernet payload from Location 2B. Figures 23 and 24 show the graphs representing the received data rate, corresponding to the transmission rate, and power received, respectively. There is no data to reflect percentage of frame loss as the Ethernet tester was experiencing some error for that calculation during this part of the experiment. Table 12 summarizes the mean and standard deviation of the available performance parameters.

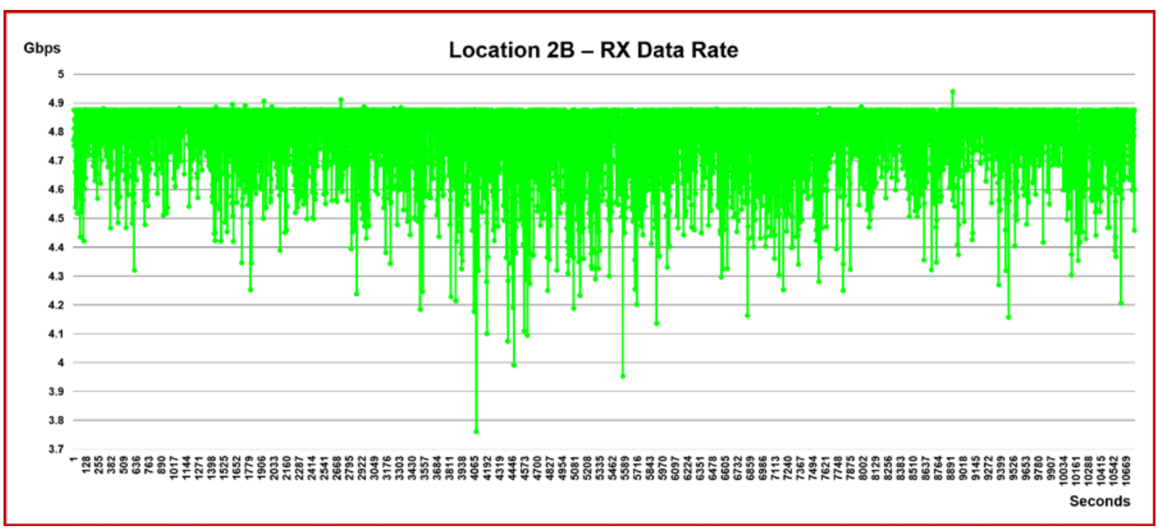


Figure 23. Received Data Rate at Location 2B

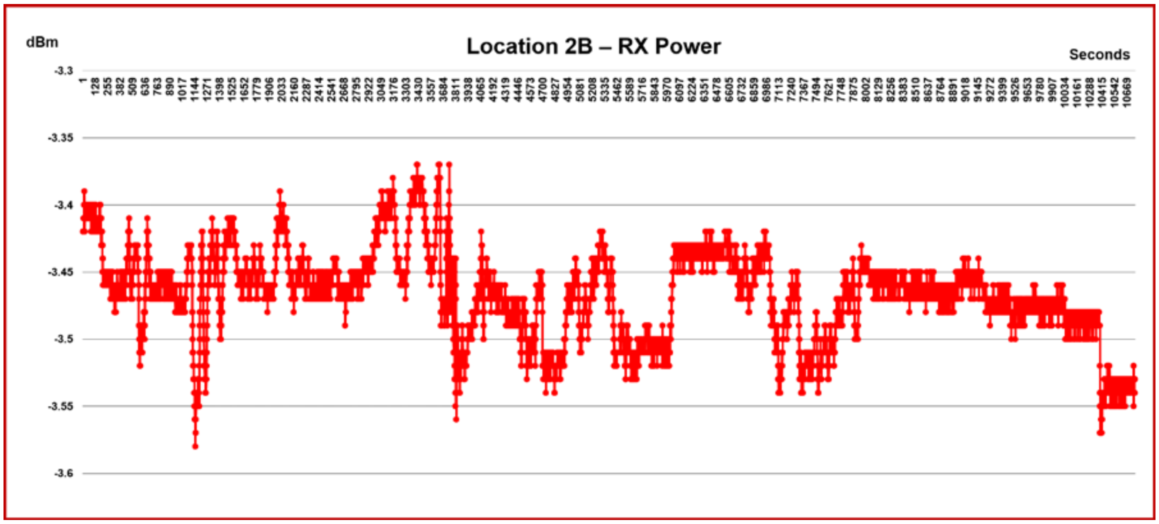


Figure 24. Received Power at Location 2B

Table 12. Mean and Standard Deviation of Performance Parameters at Location 2B

	Mean	Standard Deviation
Received Data Rate (Gbps)	4.79	0.10628
Percentage of Frame Loss (%)	NA	NA
Received Power (dBm)	-3.47	0.03282

From Table 12, the values computed for standard deviation show that the spread of data is reasonably low.

With reference to Figure 23, it can be observed that the data rate is rather stable and it follows the same pattern as that of location 2A in Figure 20. Although the graph for percentage of frame loss is unavailable, it could be assumed to be consistent with the other frame loss observations, according to the analysis of all the other data sets presented in this thesis. Its mean value should be between 1 and 2 percent. The received power fluctuates within the range of 3.35 to -3.6 dBm, providing a mean of -3.47 dBm, just under half of a milliwatt.

3. Experiment 3: 9 km Link

Figure 25 shows the locations of the two terminals for this experiment, and Figure 26 shows the elevation profile between them. It can be observed that the terminals are not obstructed by terrain, and the estimated minimum overhead clearance is about 7 meters, which is above the safety requirement. Experiment 3 was conducted between 10:00 a.m. and 12:30 p.m. on August 12, 2016. It was a clear sky with little wind. The experiment started with a temperature of 72 Fahrenheit and ended at 91 Fahrenheit.

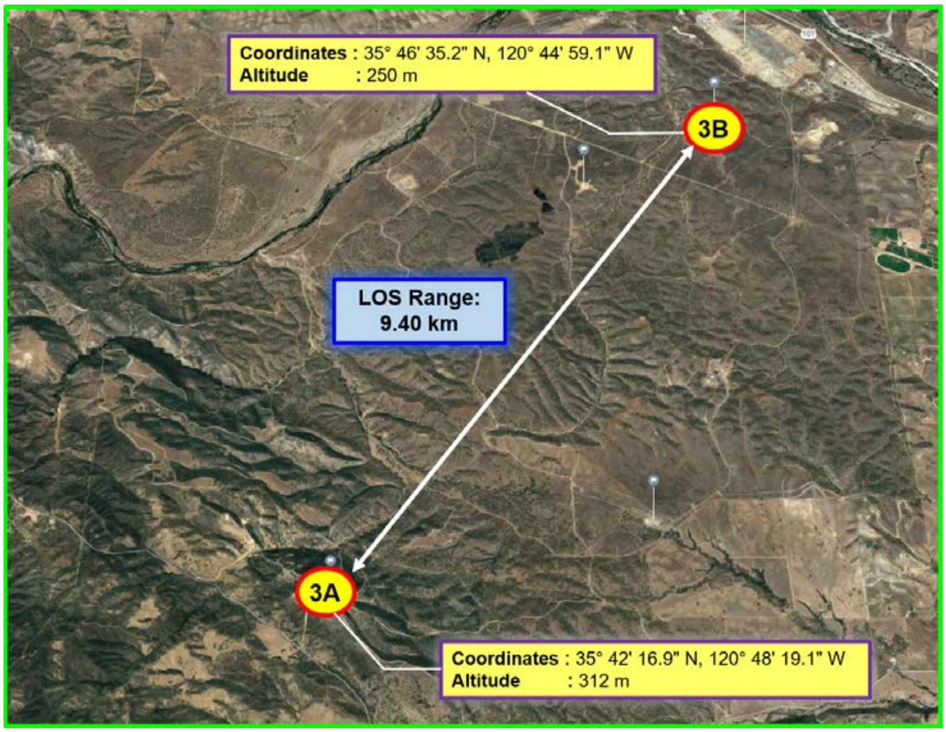


Figure 25. Locations for Experiment 3

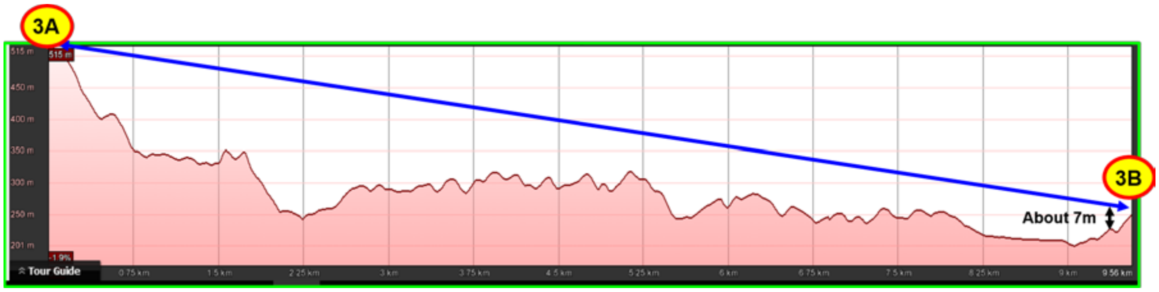


Figure 26. Elevation Profile between the Terminals for Experiment 3

a. *Results at Location 3A*

The Ethernet tester was configured to send and receive a 4.876 Gbps Ethernet payload from Location 3A. Figure 27, 28 and 29 shows the graphs representing the received data rate, the percentage of frame loss, and received power, respectively. Table 13 summarizes the mean and standard deviation of these performance parameters.

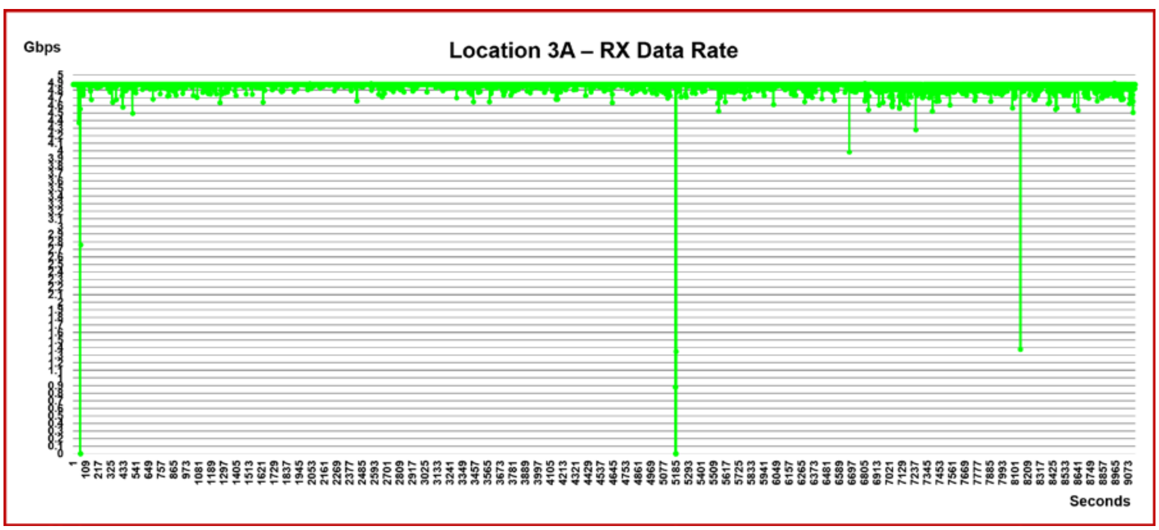


Figure 27. Received Data Rate at Location 3A

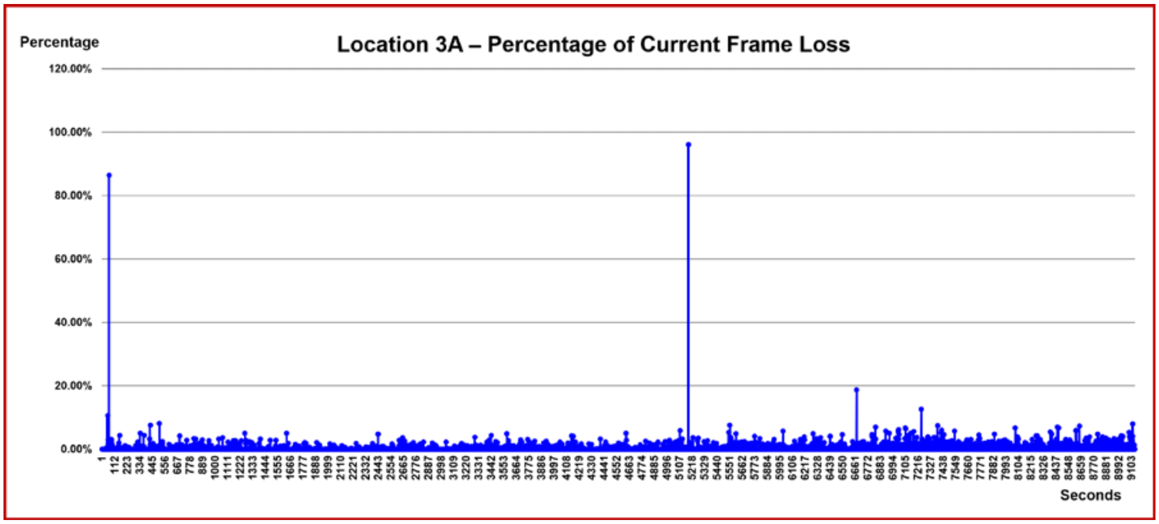


Figure 28. Percentage of Frame Loss at Location 3A

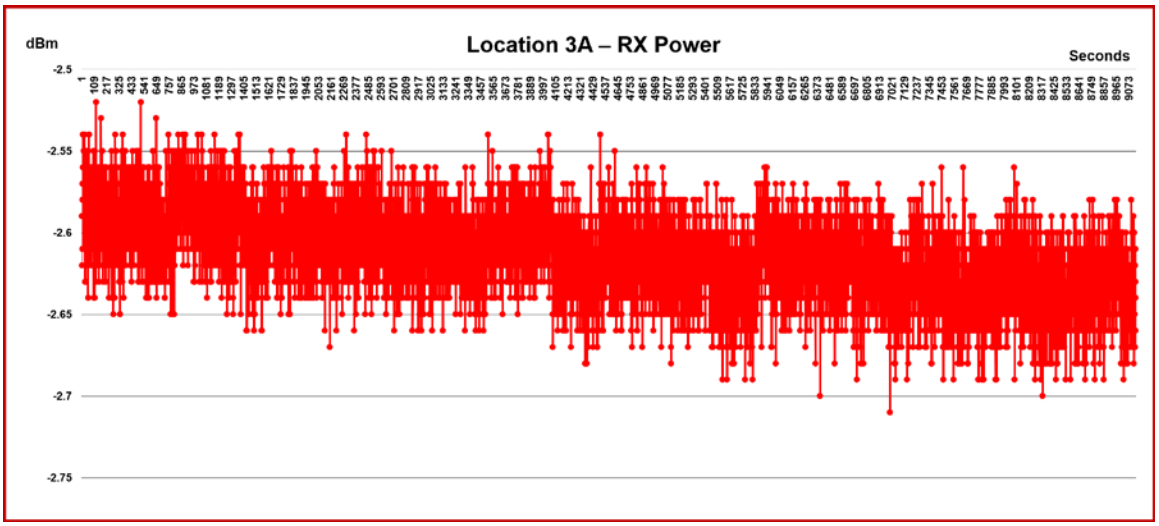


Figure 29. Received Power at Location 3A

Table 13. Mean and Standard Deviation of Performance Parameters at Location 3A

	Mean	**Standard Deviation**
Received Data Rate (Gbps)	4.86	0.17273
Percentage of Frame Loss (%)	0.23	0.01524
Received Power (dBm)	-2.62	0.02583

From Table 13, the values computed for standard deviation show that the spread of performance measure data is reasonably low.

The mean of the received data rate is very high at 4.86 Gbps. It can be observed from Figure 27 that there are two instances in which the data rate hits 0 Gbps. From the information received, the data rate plummeted to 0 for 2 seconds and 4 seconds, respectively. This dip corresponds to a spike in frame loss. The sustained frame loss resulted in a period of reduced throughput. However, the third instance of data rate dipping did not coincide with an increase in re-transmission rate. There is no corresponding evidence from the received power graph to confirm that the system had shut down. With reference to Figure 28, the percentage of frame loss is close to 0 percent during most of the experiment's duration.

It is interesting to observe that the power received at location 3A follows a trend of reduction as the time increases. This experiment was conducted from morning until mid-day. The temperature was 72 Fahrenheit when the experiment started and steadily increased to 91 Fahrenheit at the end of the day's experiment. It can be deduced that the power received decreases as the environment becomes heated up. Despite this phenomenon, the system still managed to perform effectively.

b. Results at Location 3B

The Ethernet tester was configured to send and receive a 4.876 Gbps Ethernet payload from Location 3B. Figures 30, 31 and 32 provide graphs representing the received data rate, the percentage of frame loss, and received power, respectively. Table 14 summarizes the mean and standard deviation of these performance parameters.

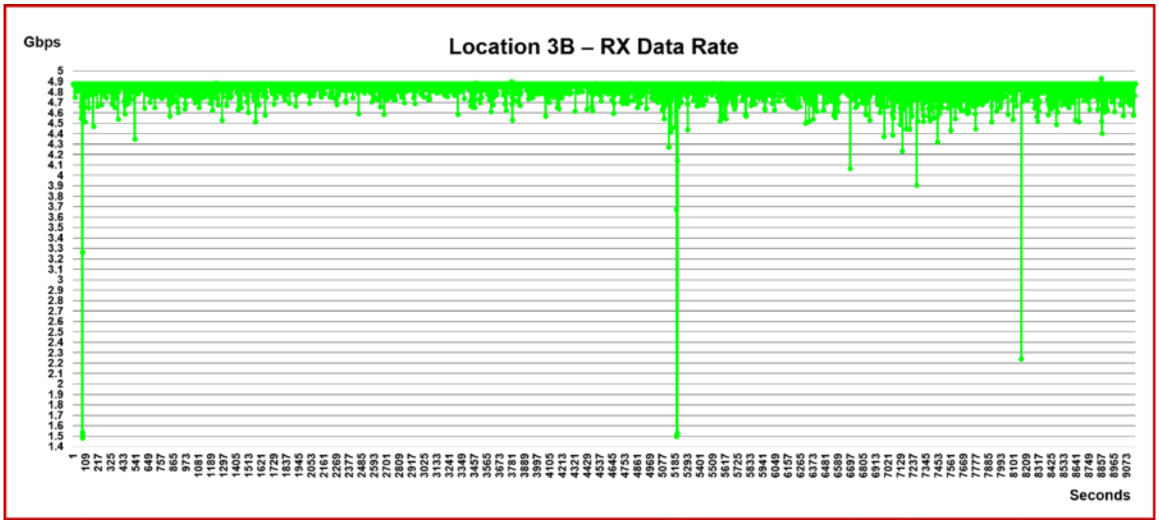


Figure 30. Received Data Rate at Location 3B

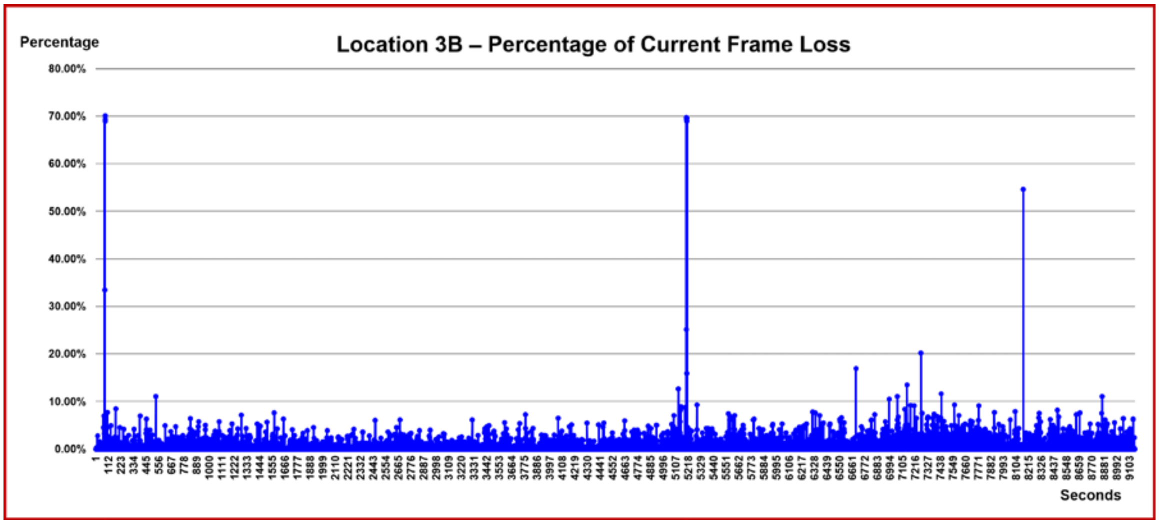


Figure 31. Percentage of Frame Loss at Location 3B

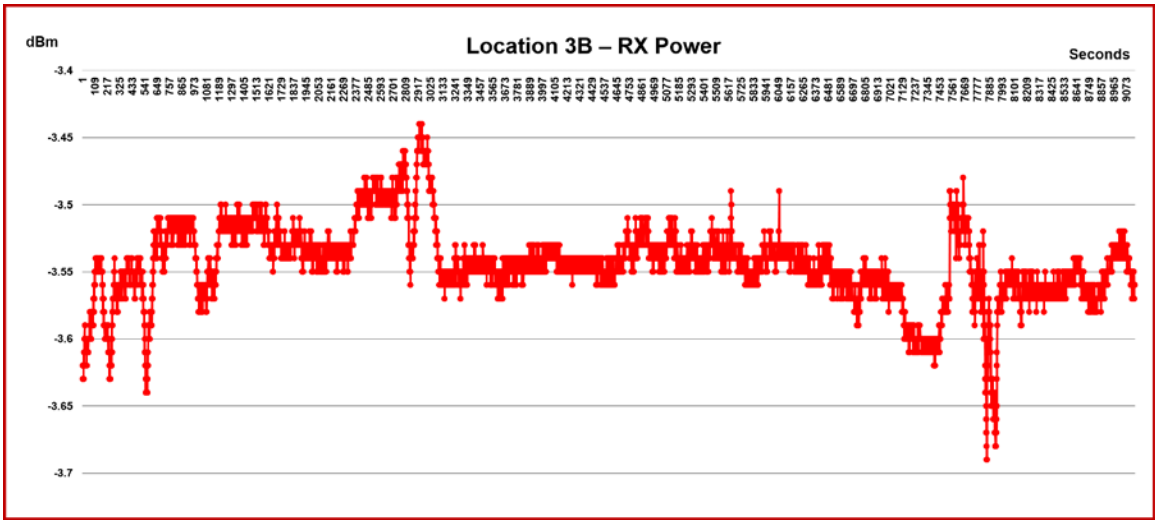


Figure 32. Received Power at Location 3B

Table 14. Mean and Standard Deviation of Performance Parameters at Location 3B

	Mean	Standard Deviation
Received Data Rate (Gbps)	4.85	0.12422
Percentage of Frame Loss (%)	0.65	0.02576
Received Power (dBm)	-3.54	0.02854

From Table 14, the values computed for standard deviation show that the spread of parametric data is reasonably low.

Similar to data analyzed at location 3A, the mean received data rate is high, at 4.85 Gbps. The three dips observed in Figure 30 correspond to the same timing as Figure 27. These three dips were resultant of the respective spikes for the percentage frame loss.

With reference to Figure 31, the percentage of frame loss has been remarkable, at close to 0 percent for the duration, except for the three instances of cited. However, the received power did not follow the same trend as Figure 29. It seems to be random and not following the time of day (from cool morning to hot noon).

D. ANALYSIS

Table 15 provides the mean values for the different locations.

Table 15. Comparison of Computed Mean Values between Locations

	Time	Range (km)	RX Data Rate (Gbps)	Percentage of Frame Loss (%)	RX Power (dBm)
Location 1A	3pm – 4:30pm	3.06	7.235	0.28	-2.585
Location 1B	3pm – 4:30pm	3.06	7.184	1.83	-3.206
Location 2A	3pm – 4:30pm	7.47	4.83	0.93	-2.63
Location 2B	3pm – 4:30pm	7.47	4.79	Not Available	-3.47
Location 3A	10am – 12pm	9.40	4.86	0.23	-2.62
Location 3B	10am – 12pm	9.40	4.85	0.65	-3.54

It can be observed that performance is better for the three parameters for all the “A” locations. The common characteristic for those locations is that they are at a higher elevation, beaming downwards to the “B” locations. It is most apparent for the percentage of frame loss and received power. The received power is between 0.6 – 0.9 dBm higher for the “A” locations.

Given the data collected, it can be observed that although the range between 3A and 3B is the longest, the performance displayed with regards to the received throughput of Ethernet payload and percentage of frame loss, by the NEXUS FSO communications system is comparable to that in the first experiment and is better than the range between 2A and 2B. This could be attributed to the third experiment being conducted in the early part of the day when the atmosphere is cooler.

From the analysis, the NEXUS FSO communication system was demonstrated to be capable of 10 Gbps data stream transmission over the link distances used for the experiments. It can also be deduced that the system requires a received power of -3.54 dBm for effective operation.

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V. CONCLUSION

This chapter provides a conclusion with respect to the stated objectives from the first chapter. Potential future work following this thesis is also discussed.

A. CONCLUSION

The thesis achieved the three key objectives of understanding FSO, designing field experiments, and conducting the designed experiment with analysis of the collected data, as mentioned in Chapter I.

FSO uses laser communication technology to establish connections between terminals. FSO enables high bandwidth that addresses today's increasing demand for greater bandwidth. Furthermore, laser technology is immune to EMI, so it is not susceptible to RF noise. It also offers a high level of communications security as it is difficult to detect and intercept when properly implemented. This is definitely an important parameter for consideration when selecting communications system for military tactical operations. However, this technology is limited to LOS communications and it is affected by atmospheric attenuation that is impossible to control. Caution has to be exercised when using an FSO communication system as the laser may cause damage to the human eye.

The preparation for this experiment included the performance of an ORM review in which a risk assessment was made for the product under trial. The SA Photonics NEXUS 3 FSO Communications System was assessed to be a safe system for use under the experiment conditions used in this research. A set of standard operating procedures was further implemented to mitigate any residual risk.

The NEXUS FSO communications system was tested during JIFX for link ranges of 3 km, 7 km, and 9 km, communicating at 7.3 Gbps, 4.8 Gbps, and 4.8 Gbps, respectively. Its performance shows a less than 5 percent decrease between the transmitted data rate and the mean received data rate ("good" throughput), a less than 2 percent mean percentage of frame loss, and a received power range difference of 0.03 mW. It can be observed that the re-transmission rate is inversely related to the received data rate.

The NEXUS FSO communications system was observed to be a highly reliable and effective laser system in the experiments conducted for this thesis. However, there is insufficient evidence to extend that conclusion for all communications situations as the data for sampling is too small. More experiments must be conducted to establish a more definite conclusion. The success of the NEXUS FSO communications system going through JIFX opens the opportunity for such experiments. The necessary work of clearing the safety requirements for laser usage and implementing a set of procedures that are tested to be operationally sound and safe has already been performed during JIFX. Finally, the NEXUS FSO communications system has shown that it is a capable system worth continued testing to further its capacity, particularly over increasing link distances.

B. POTENTIAL FUTURE WORK

From this thesis, it is evident that FSO is a communication technology worth pursuing. The successful completion of this thesis lays the ground for potential work in the future.

1. More Experiments with NEXUS FSO Communications System

The NEXUS FSO communications system proved its performance to be capable of sending and receiving 4.7 Gbps of Ethernet load using a 10 Gbps data stream over a link range of 9 km with a mean percentage frame loss of 0.23% in the conducted experiments in JIFX. It is highly recommended to conduct additional experiments to better characterize the system. Repeated

experiments at the same range and location should be conducted to collect more data for sampling. This could be used to further establish the relationship between system performance and time of day or seasonal variation, and the information could be useful for future mission planning.

Experiments with increased link range should definitely be conducted to understand the full-range capacity of the NEXUS FSO communications system. These experiments should be done according to the established experiment procedures for consistency in measurement and analysis.

2. Experiments Involving Other FSO Communication Systems

It is worthwhile to explore alternatives for a more thorough analysis regarding FSO as the next-generation means of communication for tactical operations. First, this approach will enhance better understanding of FSO systems overall, rather than restricting knowledge to just a few products. Next, it offers opportunities to other developers in the same industry a common environment to enhance development of their products' capabilities. Finally, this positive competition fosters improvement in the technology, which ultimately benefits the end-users.

The proposed process in Chapter III could be adopted to prepare the required experiments and laser clearance with the Department of the Navy Laser Safety Review Board (LSRB). In addition, a matrix could be constructed for evaluation of all the tested FSO communication systems.

3. Exploring the Possibility of Implementing Relay Capability

As previously noted, FSO is strictly an LOS communications system. However, there is hardly any clear LOS for long distances, and it is definitely a challenge that will impact mission capabilities. Therefore, a viable future work would be to explore the possibility of implementing FSO relay capability as a solution for broadband communication over the horizon in tactical operations.

Relay could be implemented from ground-to-air and air-to-ground paired links. The device in the air acts as a repeater to avoid physical obstructions during required ground-to-ground communications. This solution addresses the challenge involving LOS, and transmission away from the ground reduces the effect of atmospheric scintillation to the optical link. The solution could be cascaded to further increase the eventual ground-to-ground range. Furthermore, this may bring forth interesting discussion on how to align the connecting systems on-the-move.

APPENDIX A. SA PHOTONICS NEXUS DATASHEET

NEXUS FSO communications system was used for the experiments in this thesis. The following is a printed copy of its datasheet, from [15].

NEXUS FREE-SPACE OPTICAL COMMUNICATIONS SYSTEM

NEXUS

Nexus is a free-space optical communications system specifically designed for operation through the atmosphere, providing robust and reliable high data rate communications for stationary and on-the-move applications.

SA Photonics

130-A Knowles Drive, Los Gatos, CA 95032 | Phone: 408.376.0252 | Fax 408.376.0950 | www.saphotonics.com | email: sales@saphotonics.com

NEXUS FREE-SPACE OPTICAL COMMUNICATIONS SYSTEM

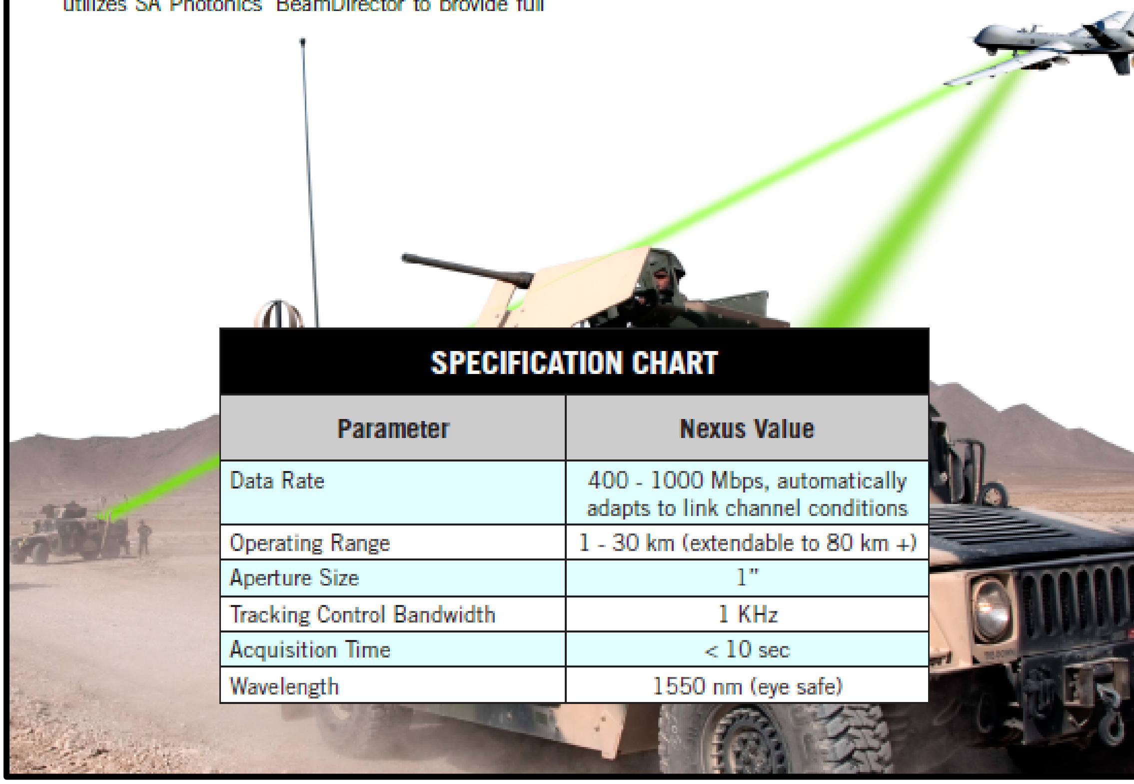
SA Photonics' Nexus is a high data rate free-space optical (FSO) communications system with several significant advantages over RF-based communication systems:

- Jam Resistant - Immune to RF jamming and interference
- Secure & Stealth - High directionality limits ability to detect and intercept
- Supports data rates that are orders of magnitude greater than RF links
- Low Size, Weight and Power (SWaP)
- Operable in spectrum constrained environments
- Supports long distance links

Designed for both terrestrial and airborne platforms, Nexus is available in two configurations: one for fixed platforms and the other for on-the-move platforms such as small unmanned aerial vehicles (UAVs) and Humvees. Nexus for on-the-move applications utilizes SA Photonics' BeamDirector to provide full hemispherical beam steering. In addition, Nexus' high bandwidth optical tracking control loop enables operation without a stabilized gimbal.

Nexus ensures robust and reliable operation throughout atmospheric turbulence and scintillation by using innovative techniques, including adaptive code rate forward error correction, physical layer retransmission, high bandwidth tip-tilt optical tracking, and autonomous acquisition and rapid re-acquisition. As a result of the combination of these techniques, SA Photonics has created a simple and compact, yet robust system that avoids the complexity and cost of adaptive optics solutions.

SA Photonics is a pioneer in the development and deployment of innovative communication and sensing solutions for military and commercial customers.



SPECIFICATION CHART

Parameter	Nexus Value
Data Rate	400 - 1000 Mbps, automatically adapts to link channel conditions
Operating Range	1 - 30 km (extendable to 80 km +)
Aperture Size	1"
Tracking Control Bandwidth	1 KHz
Acquisition Time	< 10 sec
Wavelength	1550 nm (eye safe)

APPENDIX B. SA PHOTONICS LASER PERFORMANCE PARAMETERS AND NPS LHAZ ANALYSIS FOR THE NEXUS 3 26JUL2016

The laser performance analysis for NEXUS 3 was done by NPS Laser Safety Officer, Mr. Scott Giles. Calculations were done using Laser Hazard Analysis Software (LHAZ) based on the specifications of NEXUS 3 FSO communications system.

This report provides a better understanding of NEXUS 3 FSO communications system. The results generated by this analysis was used to perform ORM for Navy LSRB clearance.

The following data is a printed copy of [17]:

The parameters provided by SA Photonics to NPS for the NEXUS 3 FSO Communications System are reviewed below:

- Wavelength: 1550 nm
- Beam Diameter: 15 mm, 1/e^2
- Power / Energy: Less than 19 dBm (clarified by SA Photonics as <90 mW)
- PRF (if pulsed): CW, not pulsed
- Beam Divergence / Beam Quality (M^2): 145 micro-radian full angle, assume M^2 = 1 (clarified by SA Photonics to be the calculated measure of Full Angle Divergence)

NPS has conducted analysis found to be helpful in assessing risks associated with this system. Appended below is an LHAZ analysis for this system with these parameters.

Viewing aids were entered as 20 x 80 mm LARGE binoculars. This established a viewing aided NOHD of 1.3 km. This hazard area will be within the

line of sight between the terminals for all proposed locations. This beam path shall be 15 feet above all terrain and structures. SA Photonics attendants at both terminals shall be watching for interlopers and shall shut down the system by radio communications should an interloper be discovered.

Beam spill for terminals more than 1.3 km apart will be below the MPE for aided viewing with LARGE binoculars. Backstops aligned with IR cameras will provide additional mitigation for beam spill. Backstops and atmospheric attenuation will provide additional mitigation for beam focusing due to scintillation.

Laser Report
AFRL 711HPW/RHDO 2.5.3.64
LHAZ Plugin 5.2.3.2
LTMC Version 3.2.2.7 / Adapter 3.1.0.19
Tuesday, July 26, 2016

Laser Name: **SA Photonics NEXUS 3**

Laser Parameters:

Wavelength:	1550 nm
Output Mode:	ContinuousWave
Average Power:	90 mW
Beam Profile:	Circular
Beam Distribution:	Gaussian
Beam Divergence:	0.145 mrad
Beam Waist Diameter:	1.5 cm
Beam Waist Range:	0

MPE Computations:

Exposure Duration:	10 s
Exposure Range:	200 cm
MPE (Eye):	1.000e-001 W/cm²
Limiting Aperture (Eye):	0.35 cm
Class 1 AEL (Eye):	9.621e-003 W
Limiting Aperture (Skin):	0.35 cm
MPE (Skin):	1.000e-001 W/cm²

Classification: Class 1M

Description:
1550nm FSO Comm link

Hazard Distances and OD Requirements:

Ocular (200 cm, Aided Viewing, Existing OD = 0)
Exposure Duration: 10 s
NOHD: 1278 m

At Viewing Distance: 200 cm
Maximum OD: 0.9
At Range OD: 0.9

Skin (10 cm, Existing OD = 0)
Exposure Duration: 10 s
NSHD: 0 m

At Exposure Distance: 10 cm
Maximum OD: 1.0
At Range OD: 0.0

Diffuse Reflection Hazard Analysis:

Laser to Target Range: 1 m
Target Reflectance: 100.00 %
Viewing Angle: 0 deg

Ocular Hazards
Exposure Duration: 10 s
NHZ: 0.0 m

At Viewing Distance: 1 m
OD Required: 0.0

Skin
Exposure Duration: 10 s
NHZ (Skin): 0.0 m

At Exposure Distance: 1 m
OD Required: 0.0

Viewing Conditions:
Atm. Attenuation Coeff: 7.9031e-07 cm-1 (1/cm)
Aided Viewing Used: True
Optics Transmittance: 70.00 %
Optics Objective Diam: 80 mm
Optics Exit Diam: 3.5 mm

Spot size has been calculated using industry standard divergence equations to be as follows:

NPS Spot Size Analysis of SA Photonics NEXUS 3 for JIFX 16-4							
Class 1 MPE (W/cm2)	0.1						
Power (W)	0.9						
Waist size (m)	0.015						
distance to waist (m)	0						
divergence (rad)	0.000145						
distance to target (km)	1	2	3	4	5	8	10
Spot size (m)	0.146	0.290	0.435	0.580	0.725	1.160	1.450
Spot size (ft)	0.48	0.95	1.43	1.90	2.38	3.81	4.76
W/cm2	0.005393	0.001359	0.000605	0.000340	0.000218	0.000085	0.000054
Percent of MPE	5.39%	1.36%	0.60%	0.34%	0.22%	0.09%	0.05%

APPENDIX C. DELIBERATE RISK ANALYSIS FOR SA PHOTONICS NEXUS 3 CLASS 1M FREE-SPACE OPTICS LASER COMMUNICATION OPERATIONS AT CAMP ROBERTS AND SAN BENANCIO RADIO TOWER (MONTEREY COUNTY PUBLIC LAND)

Appendix C was done by the NPS Laser Safety Officer, Mr. Scott Giles. Risk analysis is a requirement before any laser-related experiment can be conducted in Navy or NPS facilities or conducted by Navy or NPS personnel. Hence, it is paramount to the success of this thesis.

The author took the opportunity to discuss, with the NPS Laser Safety Officer, through the deliberate five-step process of this analysis. Concluding the discussion, the author was instilled with the required knowledge to suggest valid controls for effective mitigation of laser hazards. Some of the measures were implemented in the final experimentation plan as procedural instructions for the experiment. Eventually, the author was able to take the supervising role (ORM step 5) during the experiment.

The following is a printed copy of [16]:

Identify:

Eye damage from direct intrabeam viewing
Eye damage from viewing aids
(No equipment risks identified)

Root Causes: Under select situations, laser energy may be present above the ANSI Z136.1 Maximum Permissible Exposure limits.

Assess:

Intra-beam Viewing: Laser power in excess of the MPE is possible under the following conditions

- System power higher than Class 1 (.1W/cm2) is selected by the operator
- Energy is focused by scintillation effects and becomes focused into the eye

Viewing Aids: Laser power in excess of the MPE is possible under the following conditions even if neither of the above is present

- A sufficiently large viewing aid in the beam path, aligned with the beam path, and focused appropriately collects and focuses laser power into the eye

Personnel: Cornea burn due to IR irradiance.
Severity is **Category II– Severe Injury**
Probability is **Sub-Category A – Likely**
Risk Assessment: (I-A) 1 – Critical Risk

Make Risk Decisions:

Identify Control Options

1. Restrict emitted power to less than MPE (0.1W/cm2).

2. Reduce emitting power further to minimum needed to meet receiver requirements.

3. Prohibit viewing aids from the laser beam viewing aids hazard zone.

4. Prohibit viewing aids from the viewing aids hazard zone when laser beam is on.

5. Minimize access to the beam path by choosing an overhead path with a large terrain clearance.

6. Prohibit operations if scintillation effects are present.

7. Capture beam spot at terminal.

Determine Control effects

8. Controlling emitted power to less than MPE renders the NEXUS 3 a Class 1M laser system that is incapable of producing eye damage unless viewing aids or other focusing effects are present. This greatly reduces the severity and probability for unaided viewing and reduces the severity of aided viewing hazards.

9. Further reducing emitted power reduces range of hazard for viewing aids. This will reduce the probability and severity of aided viewing hazards.

10. Prohibiting viewing aids from the beam path when laser is on will eliminate viewing aid hazards. If done absolutely, this eliminates all but uncontrolled viewing aid probabilities.

11. Prohibiting viewing aids from the beam path when laser is on will eliminate viewing aid hazards. This eliminates all but uncontrolled viewing aid probabilities and temporal procedural error probabilities, and requires additional controls to manage temporal viewing aid use.

12. Setting the beam path overhead with significant terrain clearance can greatly increase the “reasonably foreseeable viewing distance” of uncontrolled aided viewers to 3km away from the source or more (up to the target distance of 12 km). At distances greater than 1.3 km, even the largest typical viewing aids cannot gather enough beam energy to exceed the MPE. This setup reduces the probability of an intrabeam occurrence to remote.

13. Scintillation effects can randomly focus beam energy resulting in a local momentary increase in power. Detecting scintillation and prohibiting operations while the environment produces significant scintillation effects would reduce the probability of an unfortunate scintillation focusing event to the receiver operators.

14. Due to divergence, beam spot will be incapable of creating irradiance above MPE for even the largest typical viewing aids at the terminals if they are greater than 1.3 km apart. Beyond 1.3 km, capturing the beam spot will eliminate the probability of spillover encountering a focusing event due to scintillation. Capturing the beam spot will slightly reduce the risk of an already highly improbable scintillation event.

Determine Risk Decision

- **Apply Controls 1, 2, 4, and 5**. Apply control 6 if resources are available to measure scintillations effects. Apply control 7 if it is desired to increase public perception of hazard control.

- Due to operating requirements of using spotting scopes to set up the transmitter and receiver alignment, it is not possible to remove all viewing aid operations from the beam bath absolutely (Control 3). Temporal controls (Control 4) will be required.

- Scintillation detection (Control 6) may be impossible due to the very small energy in the beam at the target. Accurate scintillation forecasting is improbable due to the local nature of the phenomenon. Due to the very small energy at the target, scintillation effects are not expected to provide enough focusing effect for long enough to reach MPE. At 10 km, a focusing effect of 2000x would be required to exceed MPE, which is thermodynamically unrealistic for more than a tiny fraction of an

instant. Damage requires 10 seconds or more of continuous power above MPE.

- Capturing the beam spot will likely provide no reduction in hazard. It may provide a perception of safe operations.

Implement Controls:

Make Implementation Clear:

15. Restrict power output at the factory before deployment with the installation of an attenuator. Apply a beam block and measure output during setup to verify beam performance. Document steps in SOP.

16. Document Control #2 in SOP.

17. Selection of sites that allow restricted access of terminals to project staff such as Camp Roberts or Monterey County Controlled Communications Areas will enable excellent control of viewing aids everywhere the beam can be reasonably expected to be encountered. Establishing an overhead beam path with at least 15' of clearance over all obstacles until target terminal can nearly eliminate unexpected viewing aids from blundering into the beam path. Operators at each terminal can monitor beam path remains clear and remove laser power from both stations by a radio communications link if threatened by an aircraft or passenger balloon. SOP process is required to disable sighting scopes before laser is turned on.

18. IR cameras may be able to detect scintillation effects at the terminal. If the beam spot is so scintillated that the spot shape cannot be determined or focus regions are sustained long enough to be physically pointed at with reasonable accuracy, restricting operations may be considered.

19. IR cameras may be able to detect spot at terminal. Almost any backstop except an IR transmitting material (like glass) will absorb the IR energy, effectively ending the beam.

Establish Accountability: SA Photonics will be responsible for generating and following an SOP incorporating these controls. SA Photonics will be responsible for all SA Photonics personnel at both terminals. Only SA Photonics personnel will perform alignment procedures with sighting scopes (with lasers secured, and vice versa). All other personnel associated with the terminal operations shall be prohibited from operating viewing aids.

Provide Support: SA Photonics will provide attenuation devices, beam blocks, power measurement equipment, terminal operators, radio communications between terminals, and IR cameras. SA Photonics shall provide backstops at terminals if desired. NPS shall provide review of SOP and access to areas selected for operation.

Employ Feedback Mechanism: Terminal operators shall monitor beam path, independent initial power measurements before removing beam blocks, and built-in sensors detecting transmitted and received beam power levels throughout operations. All participants should be empowered with Safety Time-Out procedures to halt beam operation if concerns arise. SOP refinement recommendations can be directed to the Points of Contact listed in the SOP.

Supervise:

Monitor: SA Photonics terminal operators required at both terminals. Observe terminals are at least 1.3 km apart. By SOP note transmitted power to be below .1W/cm2 before removal of beam blocks. Observe beam path remains clear. Check radio communications periodically.

Review: None required unless project leads change, Navy LSRB provides additional guidance, or feedback is collected.

Recommendations:

- Conduct operations employing Controls 1, 2, 4, and 5. Apply controls 6 and 7 if resources are available.

Amplifying data:

Without mitigation, the residual risk is II-A, or Risk Assessment Code 1.
With mitigation the residual risk for personnel moves to III-D, or Risk Assessment Code 5.

Risk Assessment Matrix		PROBABILITY Frequency of Occurrence Over Time			
		A Likely	B Probable	C May	D Unlikely
I	Loss of Mission Capability, Unit Readiness or Asset; Death	1	1	2	3
II	Significantly Degraded Mission Capability or Unit Readiness; Severe Injury or Damage	1	2	3	4
III	Degraded Mission Capability or Unit Readiness; Minor injury or Damage	2	3	4	5
IV	Little or No Impact to Mission Capability or Unit Readiness; Minimal Injury or Damage.	3	4	5	5

Risk Assessment Codes
1 – Critical **2** – Serious **3** – Moderate **4** – Minor **5** – Negligible

Risk Assessment Matrix: Risk to personnel will be mitigated to Risk Assessment Code 5 (IV-D) – Negligible. Risk to Equipment will remain at Risk Assessment Code 4 (II-D) – Minor.

SEVERITY

Category I - The hazard may cause **death, loss of facility/asset, or mission failure.**

Category II - The hazard may cause **severe** injury, illness, property damage, or serious mission degradation.

Category III - The hazard may cause **minor** injury, illness, property damage, or minor mission degradation.

Category IV - The hazard presents a **minimal** threat to personnel safety or health, property, or mission.

PROBABILITY

Sub-Category A - **Likely to occur immediately** or within a short period of time. Expected to occur frequently to an individual item or person or continuously to a fleet, inventory or group.

Sub-Category B - **Probably** will occur in time. Expected to occur several times to an individual item or person or frequently to a fleet, inventory or group.

Sub-Category C - **May** occur in time. Can reasonably be expected to occur some time to an individual item or person or several times to a fleet, inventory or group.

Sub-Category D - **Unlikely** to occur.

APPENDIX D. EXPERIMENTATION PLAN FOR NEXUS 3 FSO COMMUNICATIONS SYSTEM (JIFX IN CAMP ROBERTS, 10-12 AUGUST 2016)

Combining the experimentation goals and knowledge pertaining risk analysis, the author designed the following experimentation plan for NEXUS 3 FSO communications system. This plan was executed and verified to be functional and safe for both personnel and equipment.

1. EXPERIMENTATION OBJECTIVES

The key objective that the experiment aims to achieve are to test the network performance of NEXUS 3 FSO communications system over varying distances. Experiments will be conducted according to the agreed operating procedures for link distances ranging 3 – 10km.

The team also targets to provide a positive demonstration of NEXUS capabilities while adhering to the established SOPs cleared by the Department of the Navy Laser Safety Review Board.

2. EXPERIMENTATION SCOPE

As the experimental duration is limited, only 3 link ranges (3km, 7km and 9km) will be conducted during JIFX (10 – 12 August 2016). The scope is also limited to packet losses and sustained data rate.

3. EXPERIMENTATION SETUP

The proposed setup for the required experiments and the list of items and their individual purposes are shown in Figure 33 and Table 16 respectively.

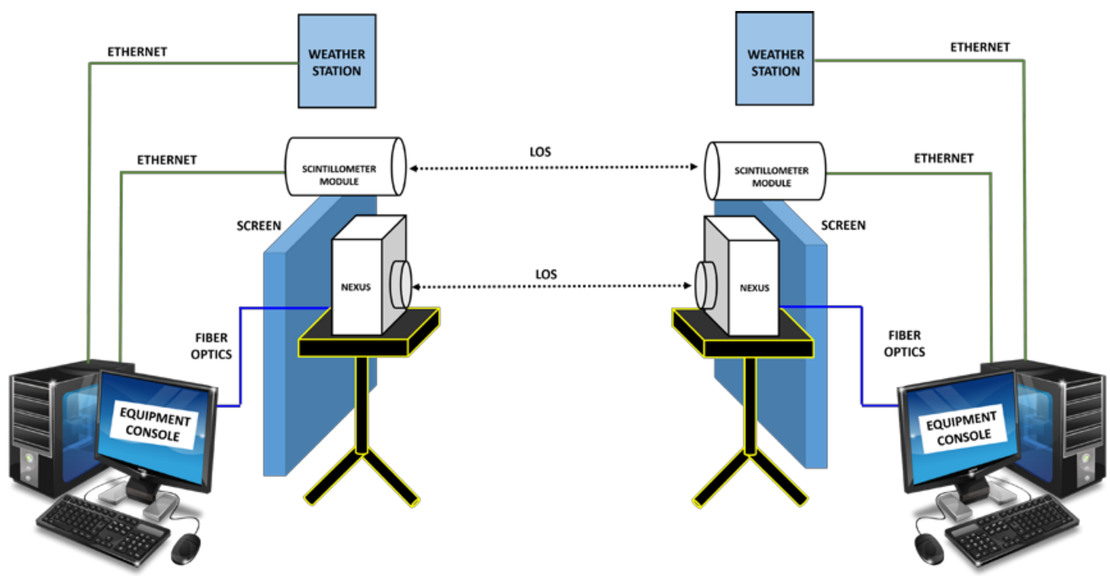


Figure 33. Proposed Setup for Experiments

Table 16. List of Items and Their Purposes

S/N	ITEM	DESCRIPTION
1	NEXUS	- FSO communications system being explored - Capable of both transmitting and receiving data - Connected to the equipment console using fiber optics cable
2	Scintillometer Module	- Measures atmospheric scintillation - Connected to the equipment console using an Ethernet cable
3	Weather Station	- Measures atmospheric information - Connected to the equipment console using an Ethernet cable
4	Equipment Console	- Set parameters of NEXUS - Attached to an external Ethernet tester - Monitors and logs parameters and measurements of NEXUS, the scintillometer module and weather station

4. PROCEDURAL INSTRUCTIONS

After setting up the equipment according to the setup shown in Figure 33, the following steps provided in Table 17 are to be followed:

Table 17. Experiment Procedural Instructions

STEP	DESCRIPTION	REMARKS
1	Ensure power is switched OFF.	Prevent damage of eyes during alignment.
2	Use rifle scope to align both NEXUS modules.	Establish LOS.
3	Establish radio communications with team from opposite terminal.	Ensure communication.
4	Block the transmitter of NEXUS module.	Prevent damage of eyes due to power being over stated range.
5	Power ON NEXUS and measure output power to ensure similar reading as equipment console.	Ensure accuracy of power reading on equipment console.
6	Power OFF NEXUS and remove blocking screen (in front of transmitter).	Preparation for start of experiment.
7	Establish radio communications (team from opposite terminal and JIFX coordinator) to illustrate intention to commence experiment and wait for “go-ahead” from all parties.	Ensure communication and common understanding.
8	Reminder to team members to prohibit use of viewing aids such as binoculars.	Prevent damage of eyes due to viewing aids.
9	Power ON NEXUS and start logging.	Start of experiment.
10	Maintain communications throughout experiment.	Ensure communication.

5. EXPERIMENT 1: 3km LINK RANGE

The information for the locations for experiment 1 is stated in Figure 34.

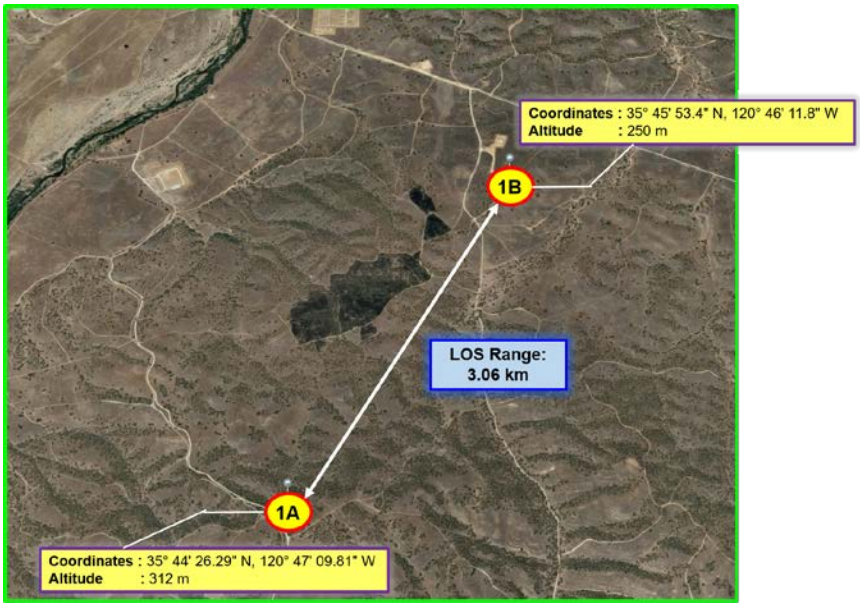


Figure 34. Locations for Experiment 1

6. EXPERIMENT 2: 7km LINK RANGE

The information for the locations for experiment 2 is stated in Figure 35.

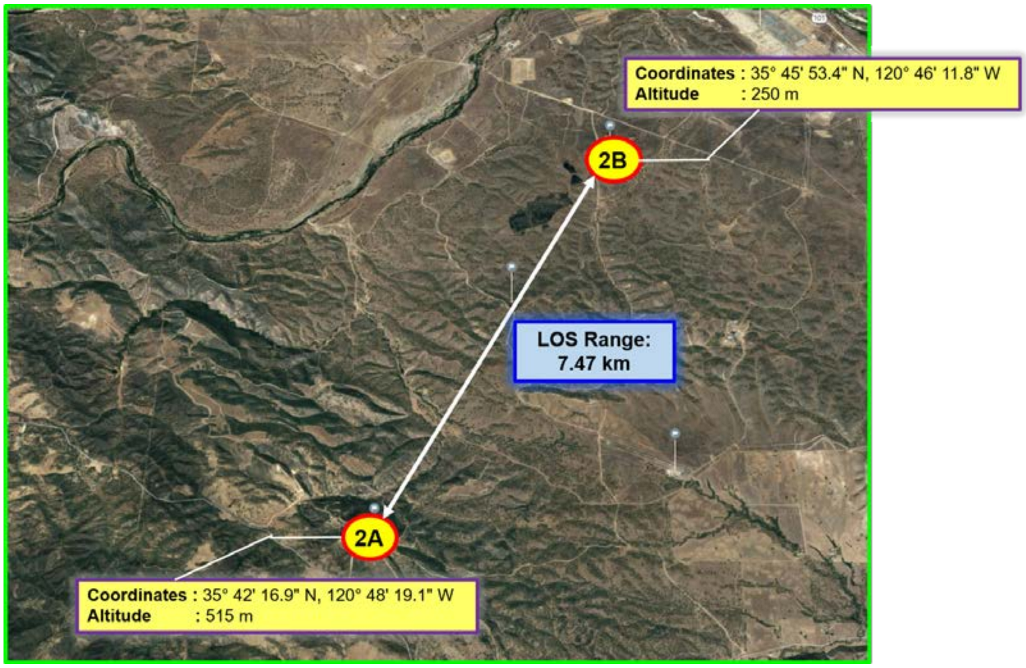


Figure 35. Locations for Experiment 2

7. EXPERIMENT 3: 9km LINK RANGE

The information for the locations for experiment 3 is stated in Figure 36.

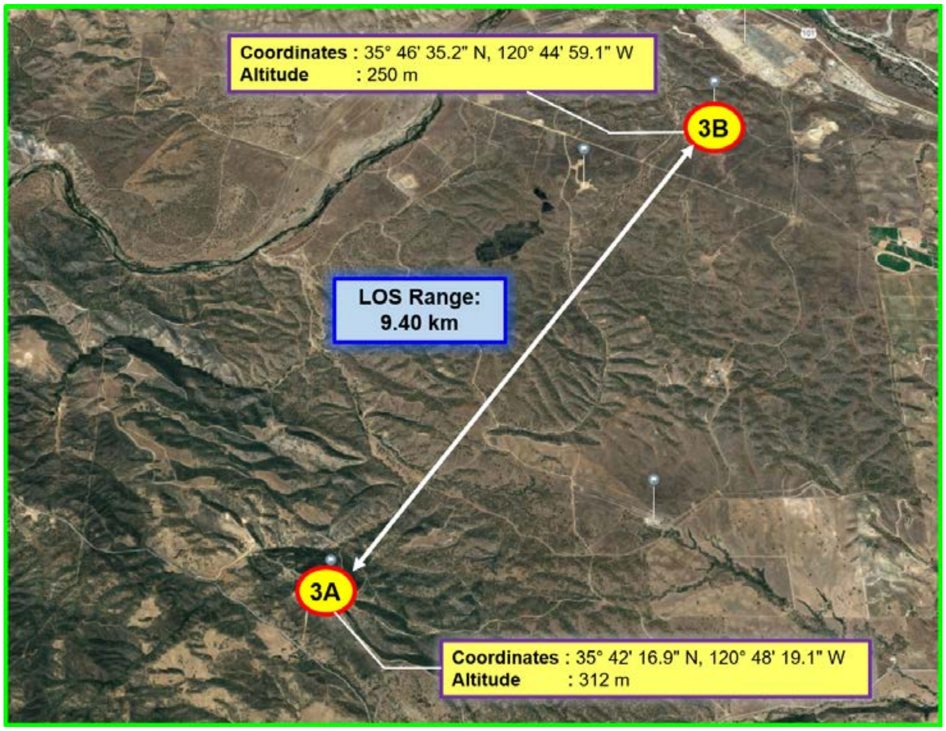


Figure 36. Locations for Experiment 3

8. RESULTS

For each experiment, record the transmitted data rate, log the performance parameters of NEXUS FSO communications system, weather station data and scintillometer data.

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